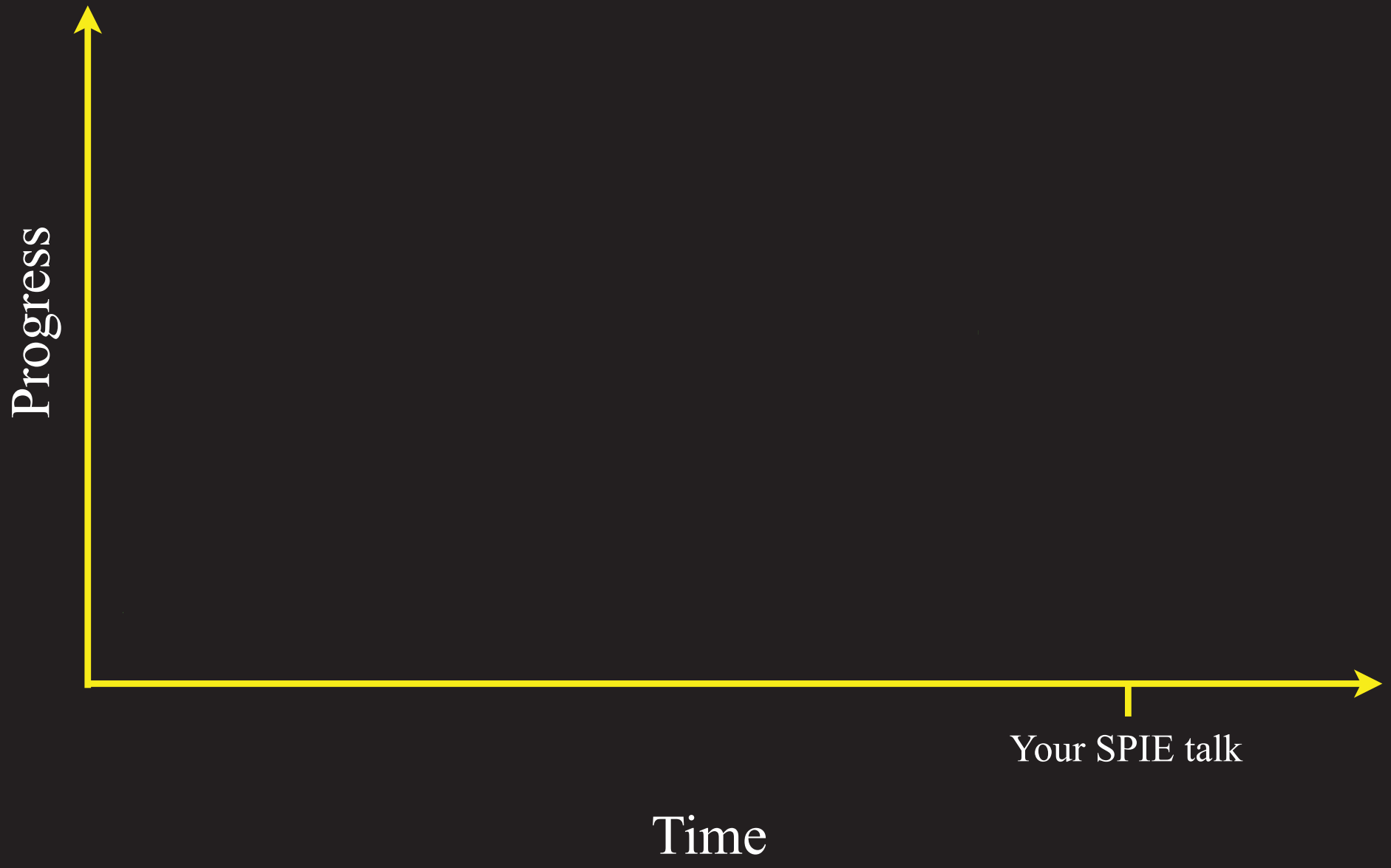
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Electric field reconstruction in the image plane of a high-contrast coronagraph using a set of pinholes around the Lyot plane

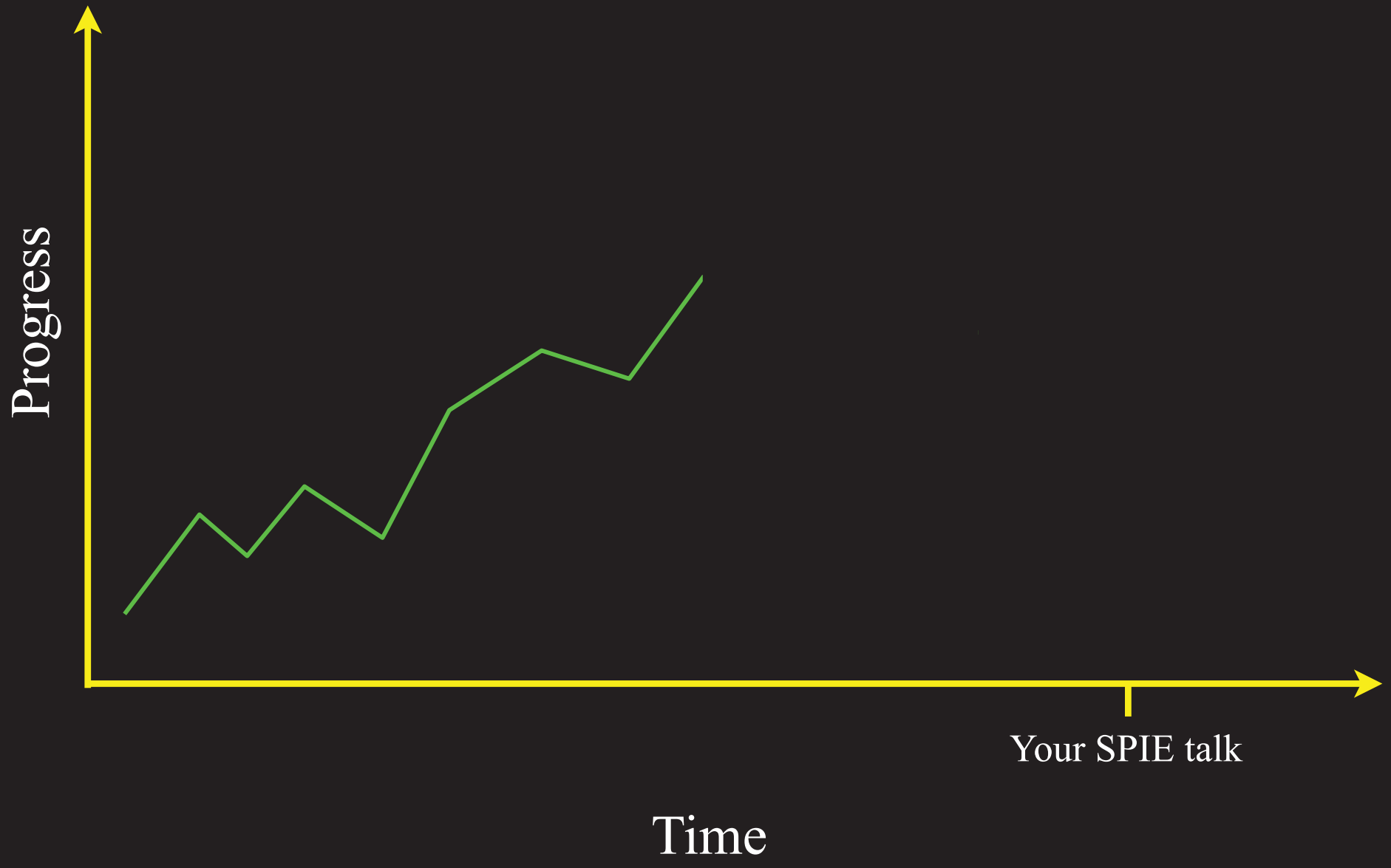
Amir Give'on
Jet Propulsion Laboratory
California Institute of Technology, Pasadena CA

Co-authors: Brian Kern, Stuart Shaklan, Kent Wallace, Charley Noecker

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

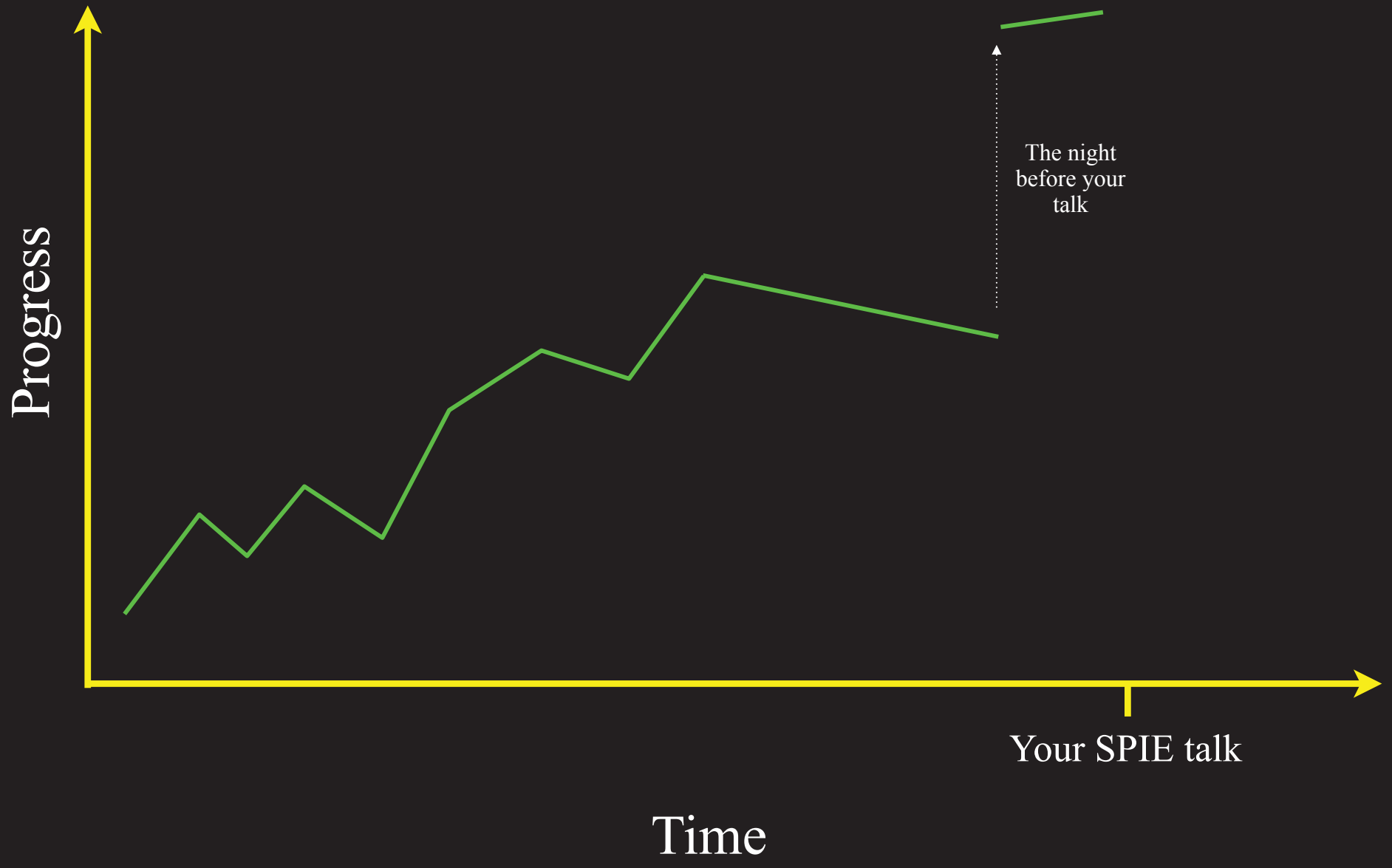


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



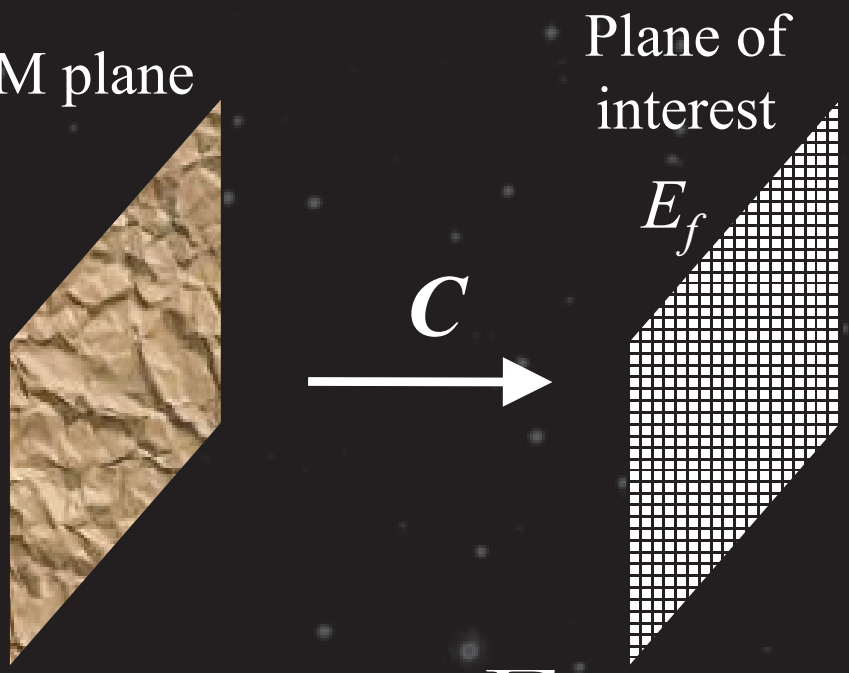
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Electric Field Conjugation

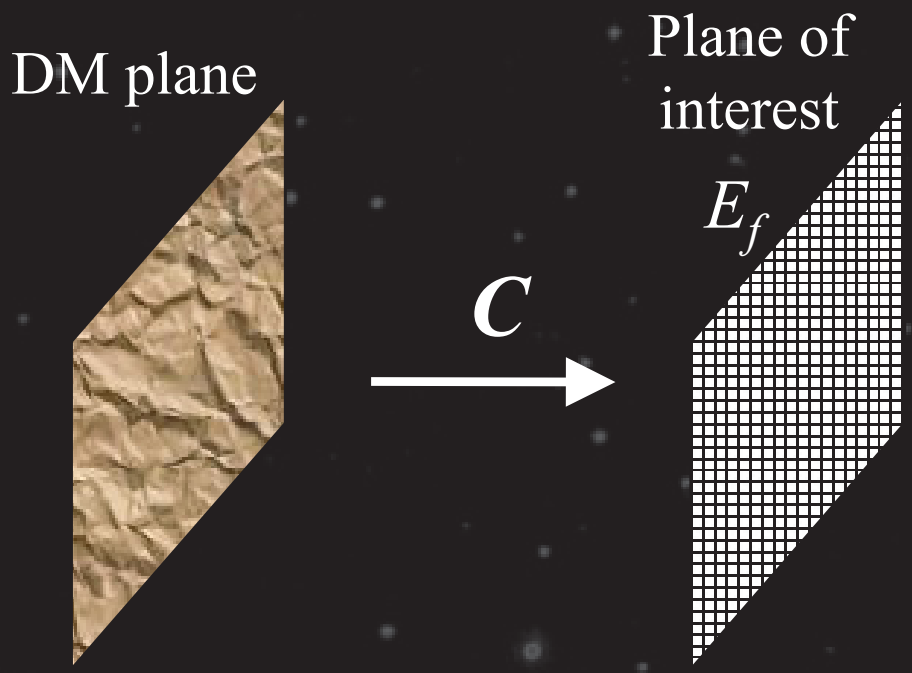


$$E_{abr+ideal}$$

$$E_f =$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

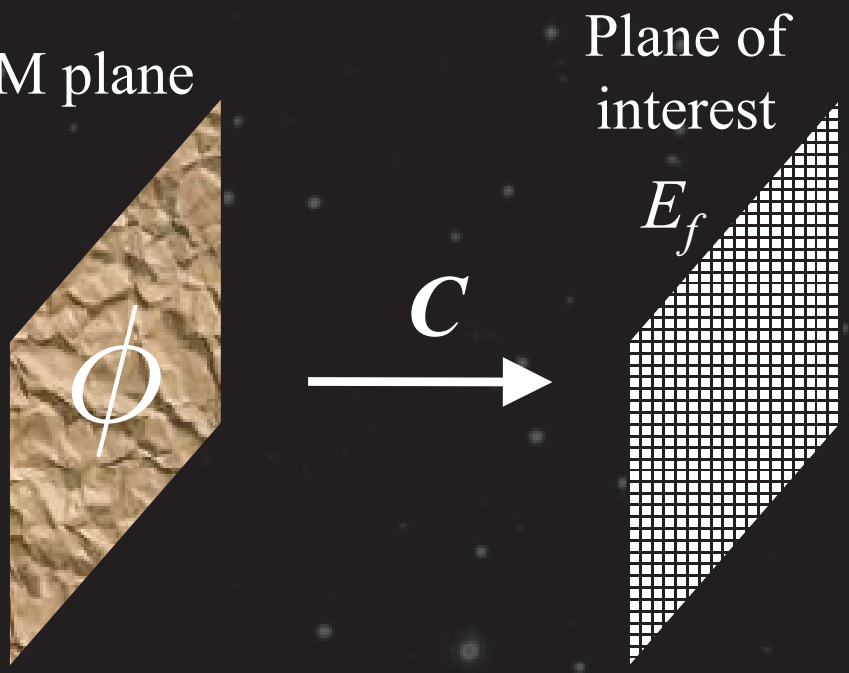
Electric Field Conjugation



$$E_f = E_{abr+ideal}$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

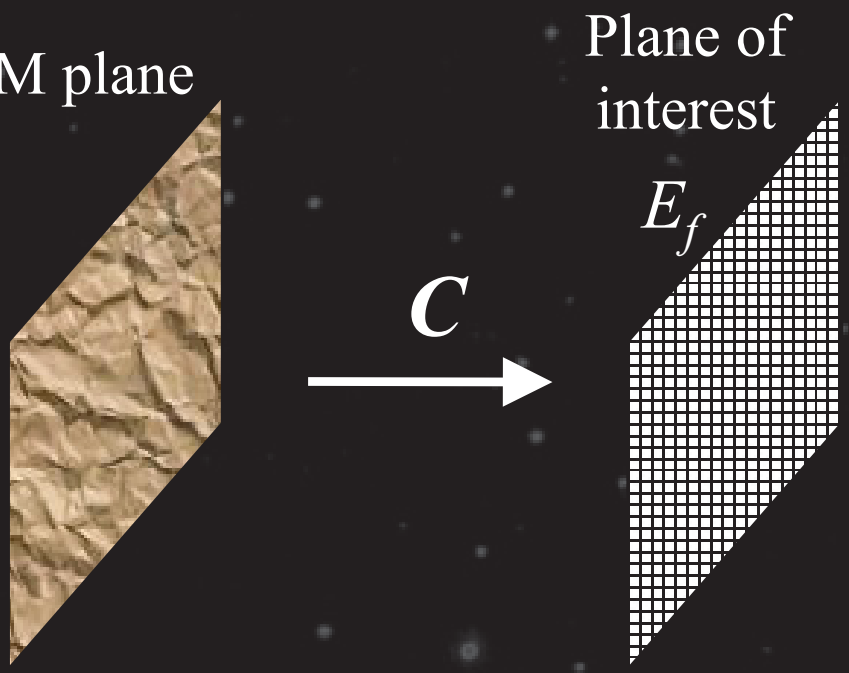
Electric Field Conjugation



$$E_f = E_{abr+ideal}$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

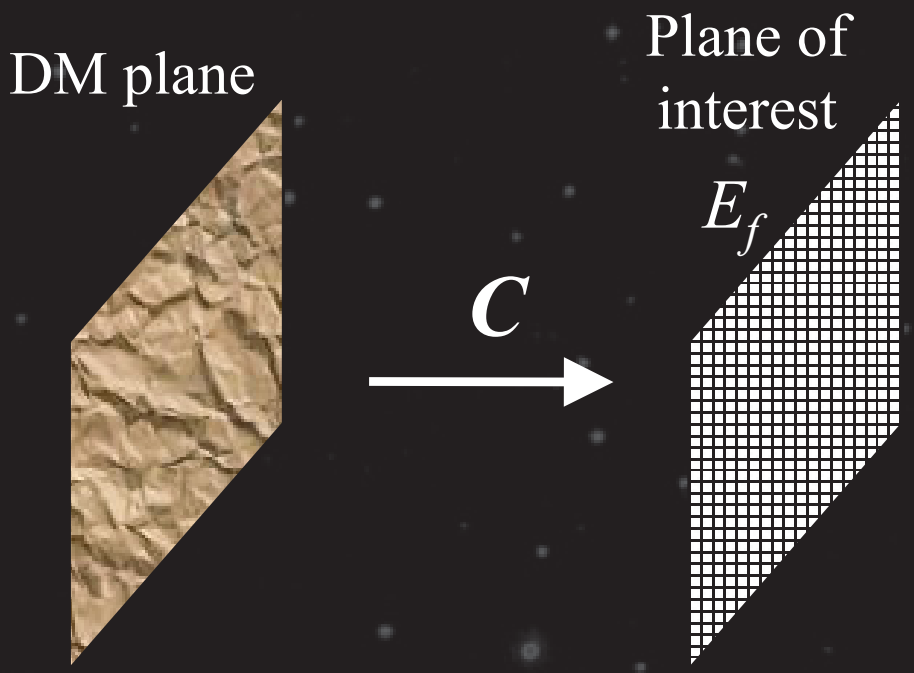
Electric Field Conjugation



$$E_f = E_{abr+ideal} + E_{DM}$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Electric Field Conjugation

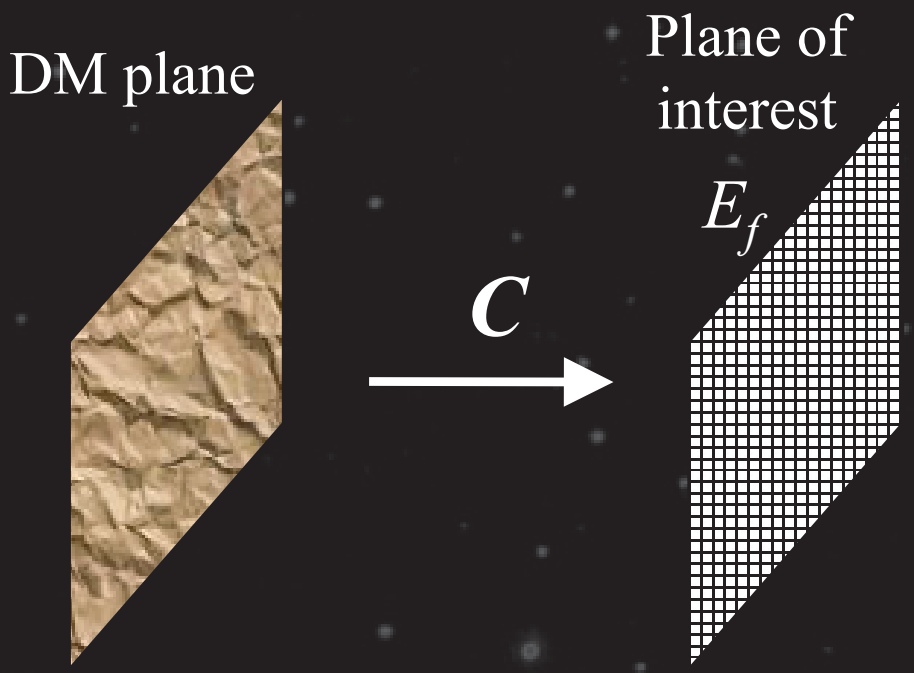


Find the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations

$$E_f = E_{abr+ideal} + E_{DM} = 0$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Electric Field Conjugation



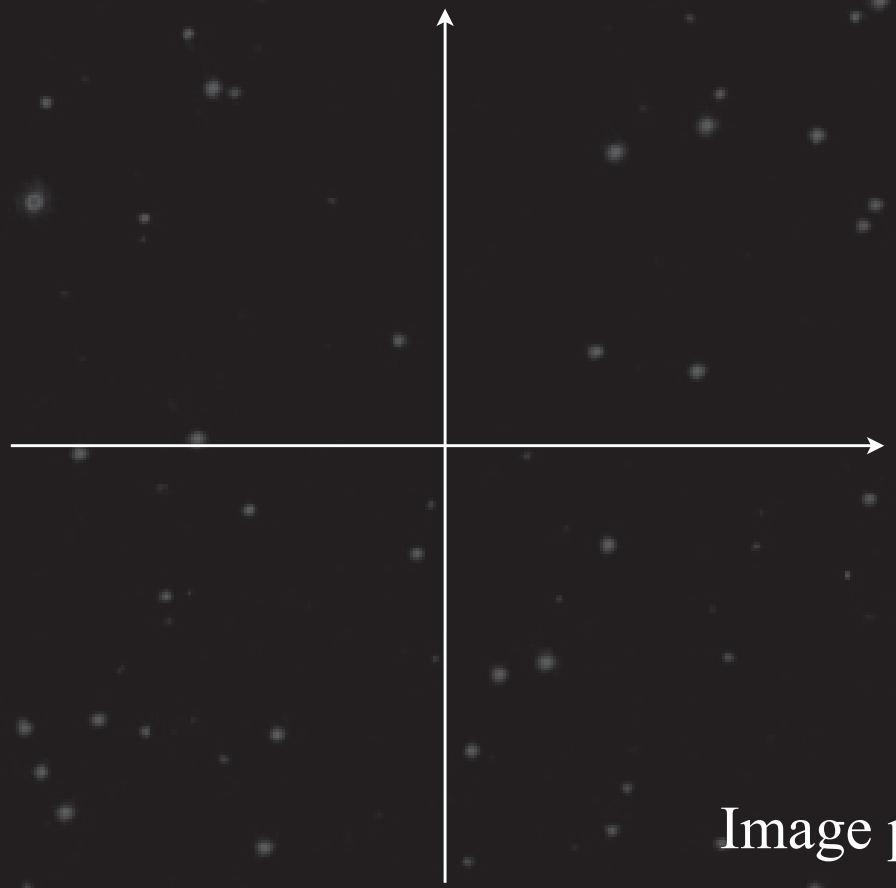
Find the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations

$$E_f = E_{abr+ideal} + E_{DM} = 0$$

Linearize w.r.t actuators heights

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

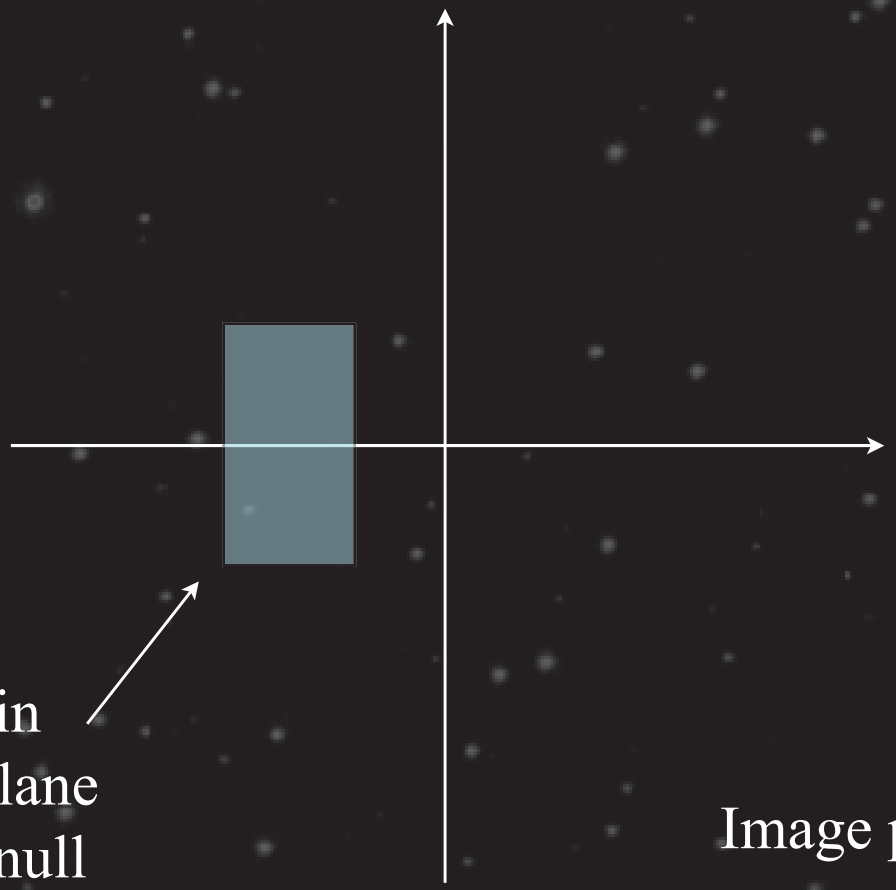
What shapes on the DM should we use for the probes?



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

What shapes on the DM should we use for the probes?

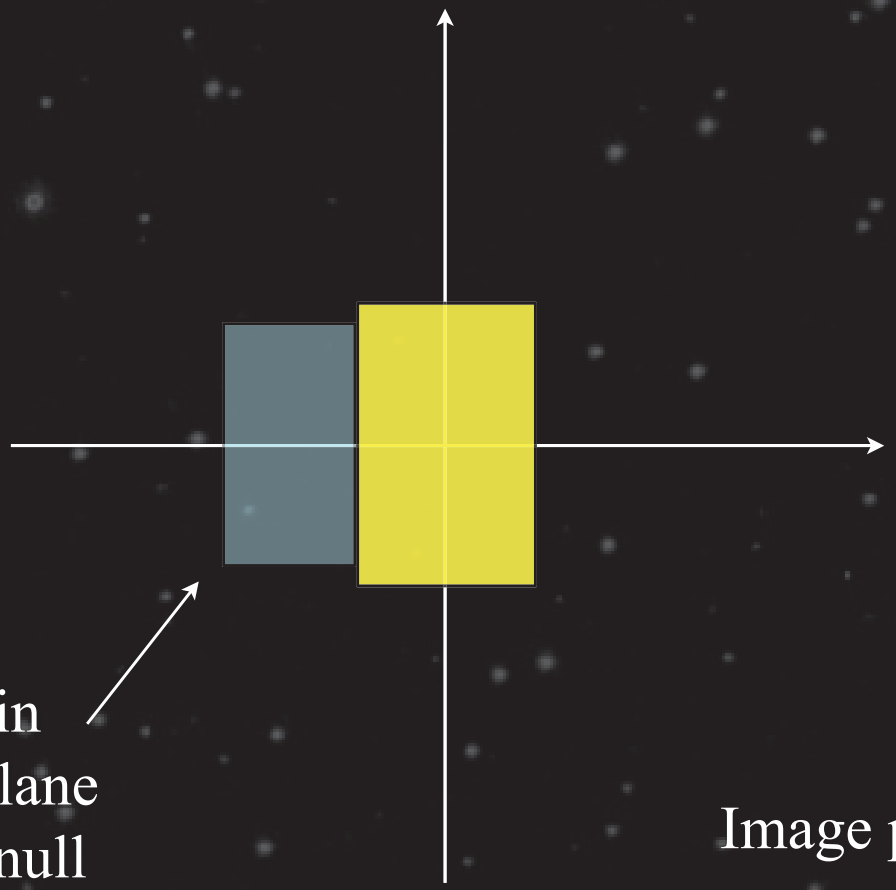
$$DM(x, y) = ?$$



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

What shapes on the DM should we use for the probes?

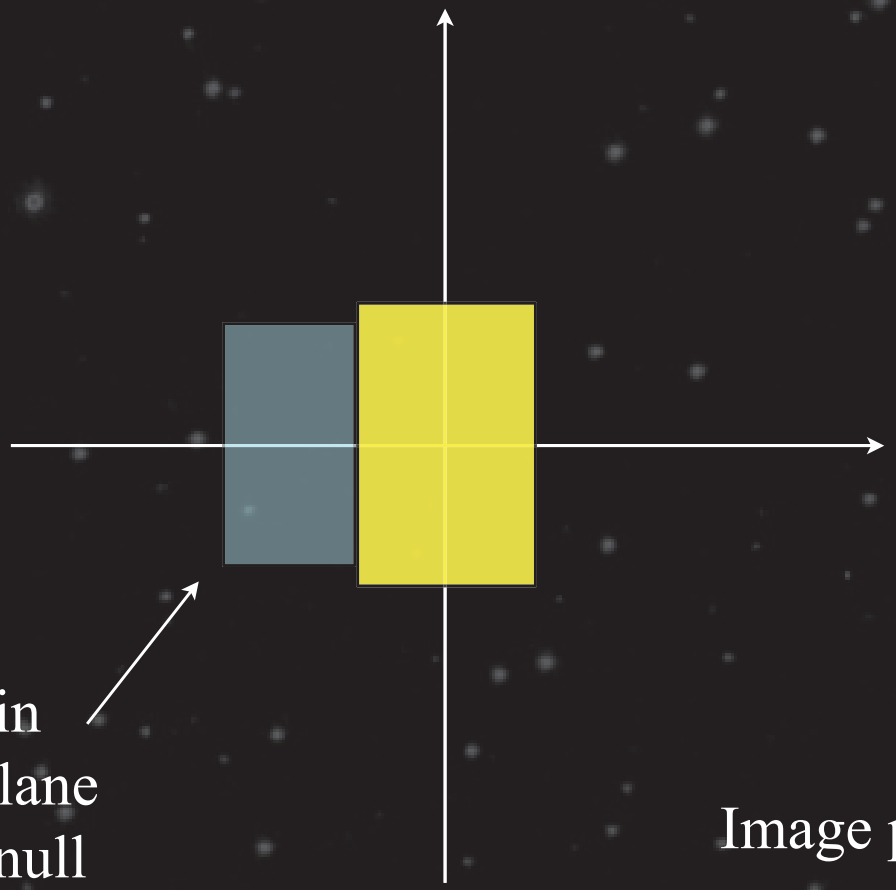
$$DM(x,y) = sinc(w_x x)sinc(w_y y)$$



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

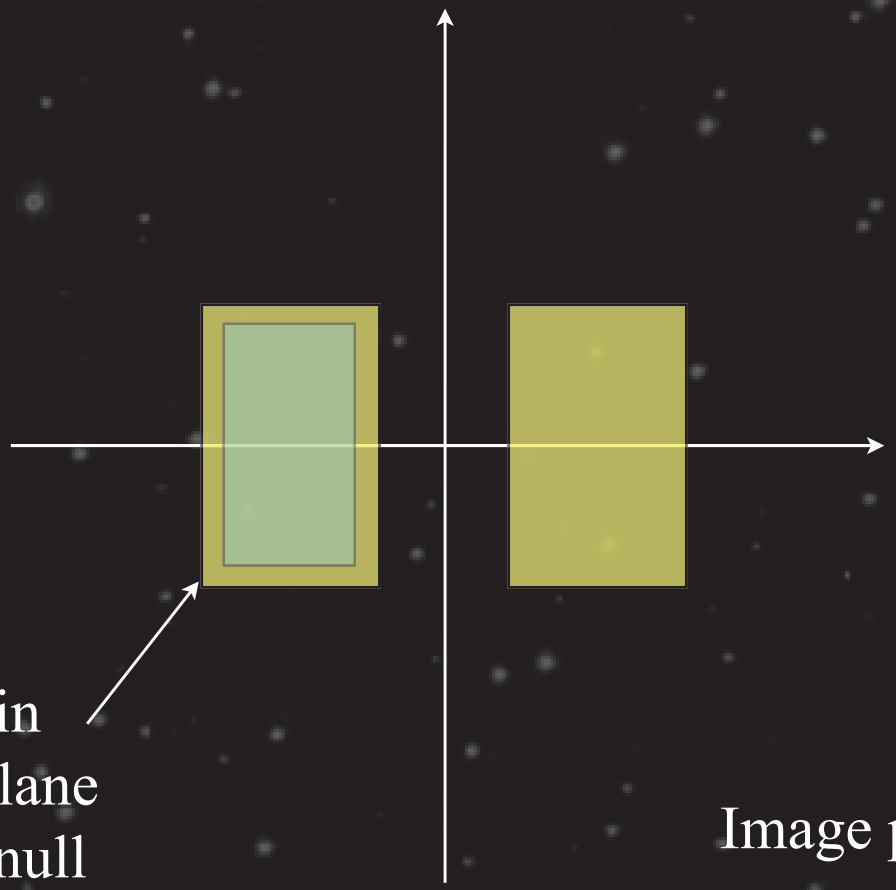
What shapes on the DM should we use for the probes?

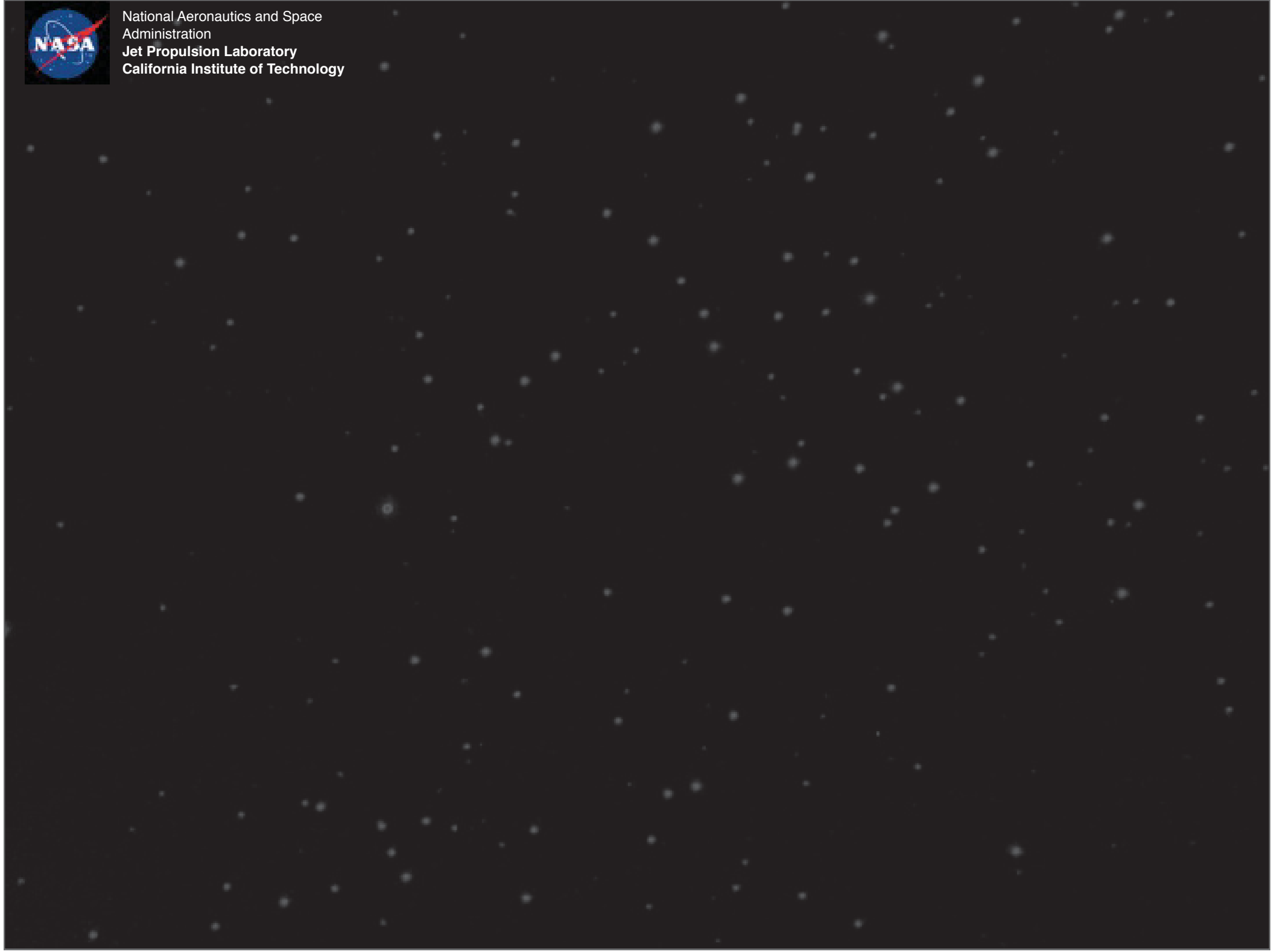
$$DM(x,y) = sinc(w_x x)sinc(w_y y)cos(f_x x + \phi)$$



What shapes on the DM should we use for the probes?

$$DM(x,y) = sinc(w_x x)sinc(w_y y)cos(f_x x + \phi)$$

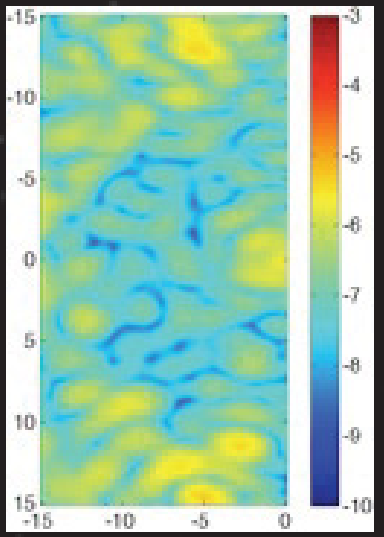




Monday, June 25, 2012

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

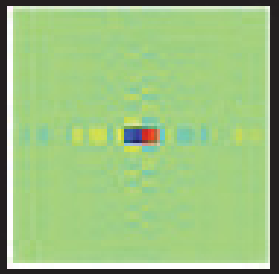
Measured intensity

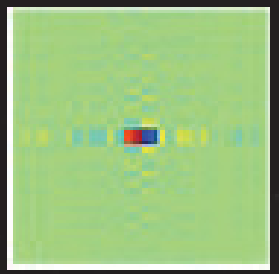


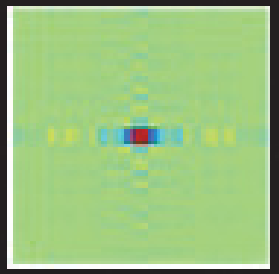
Monday, June 25, 2012

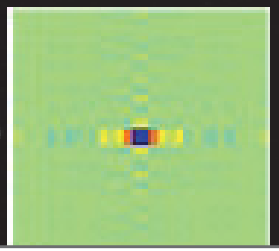
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

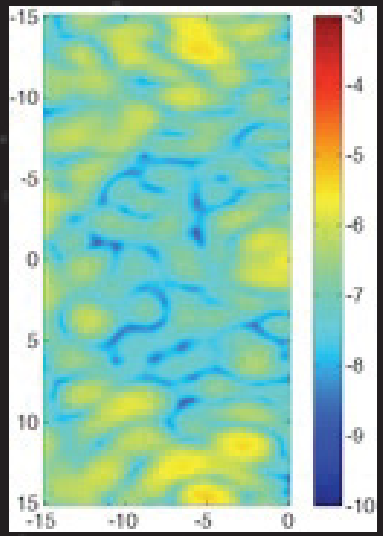








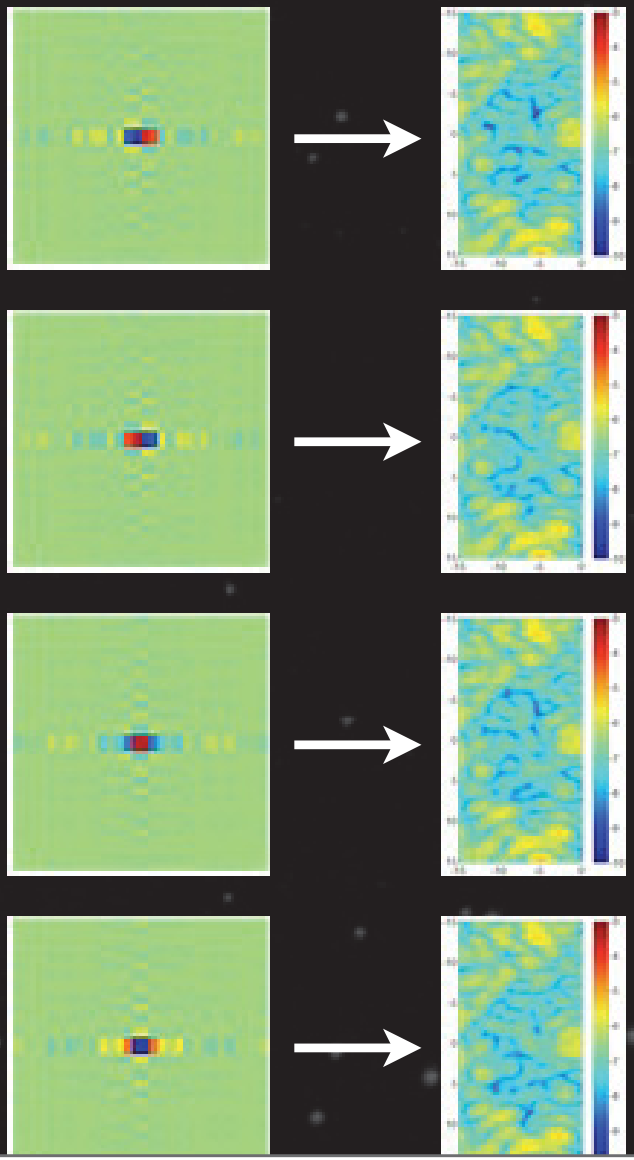
Measured intensity



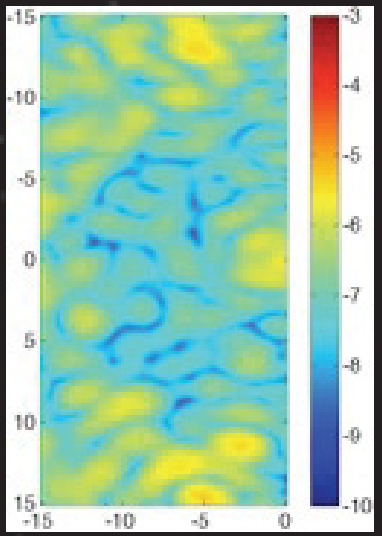
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

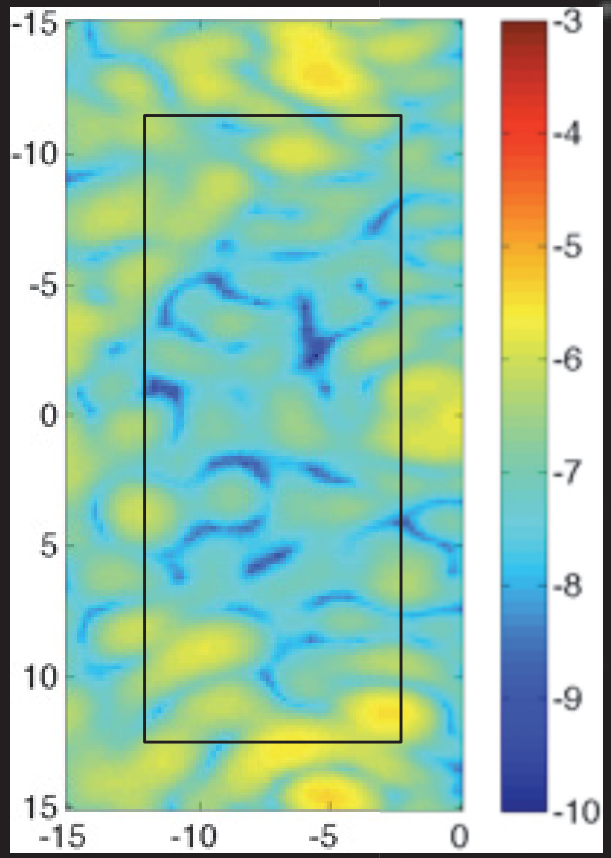
Probe images



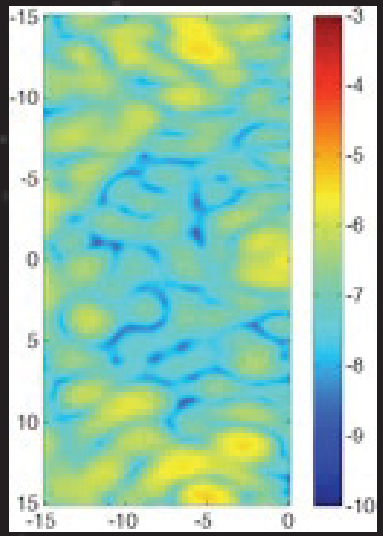
Measured intensity



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



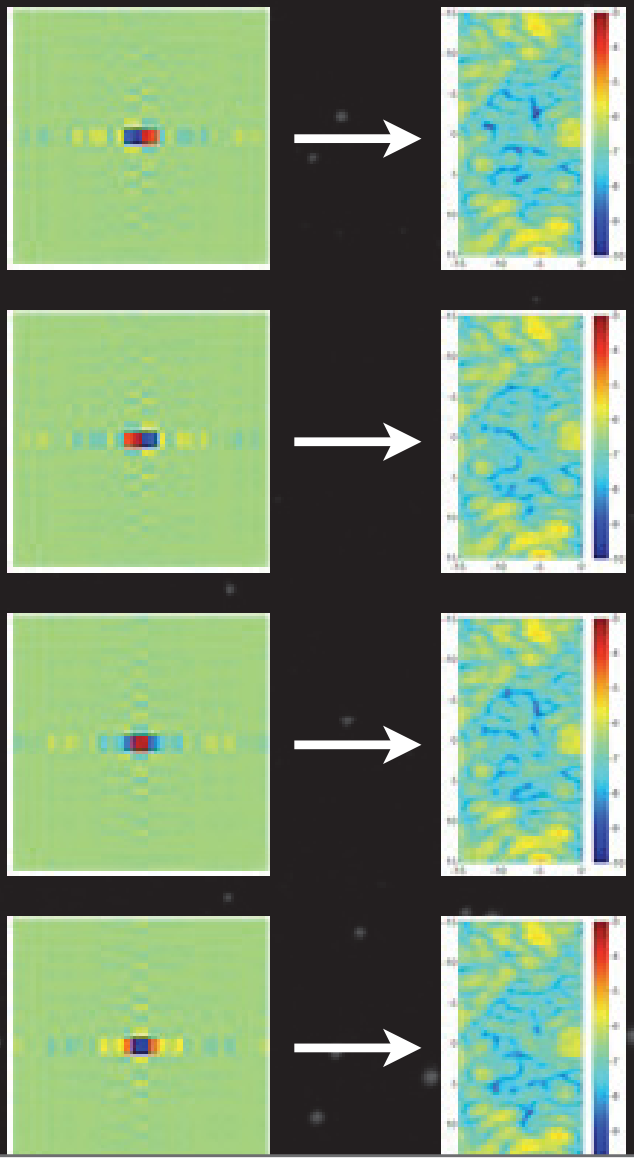
Measured intensity



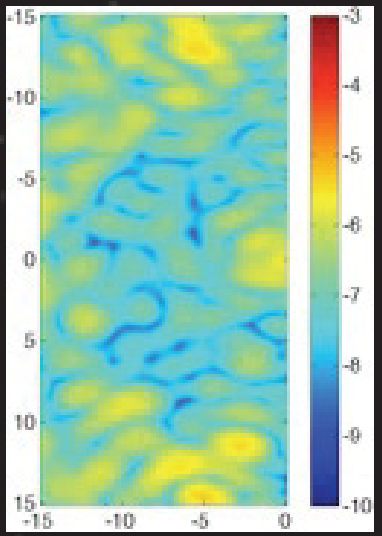
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

Probe images



Measured intensity



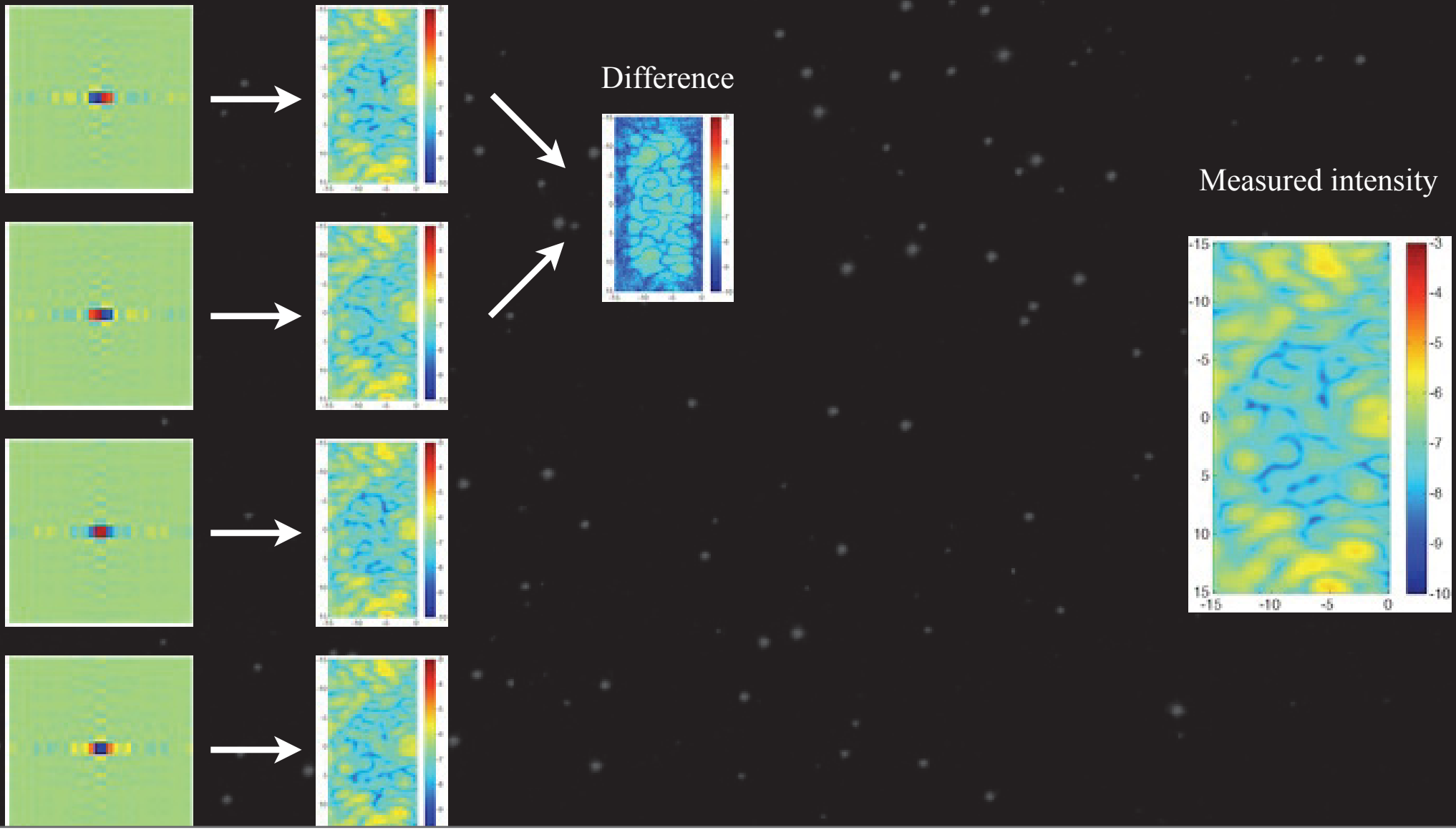
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

Probe images

Difference

Measured intensity



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

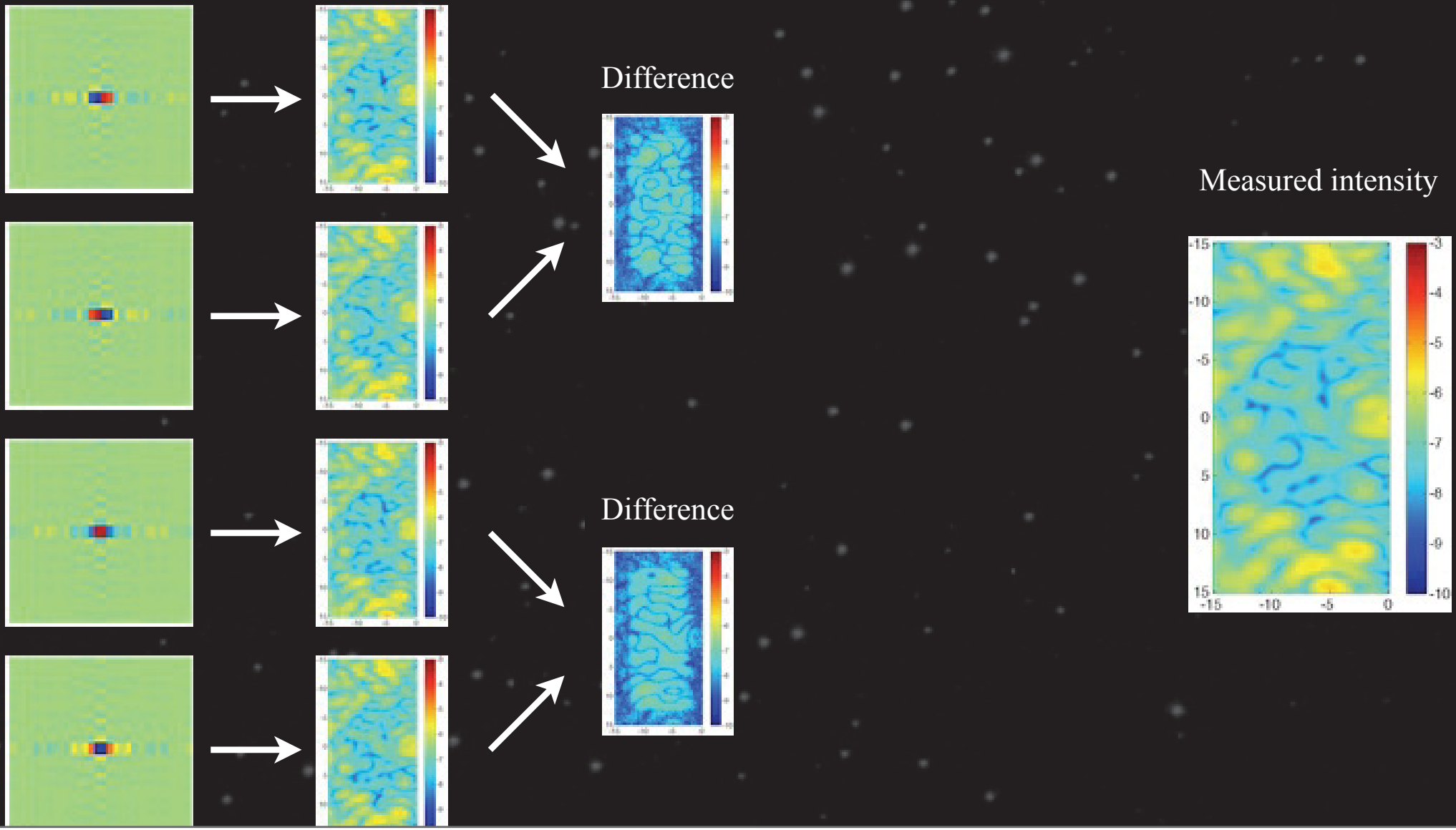
DM voltages

Probe images

Difference

Difference

Measured intensity



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

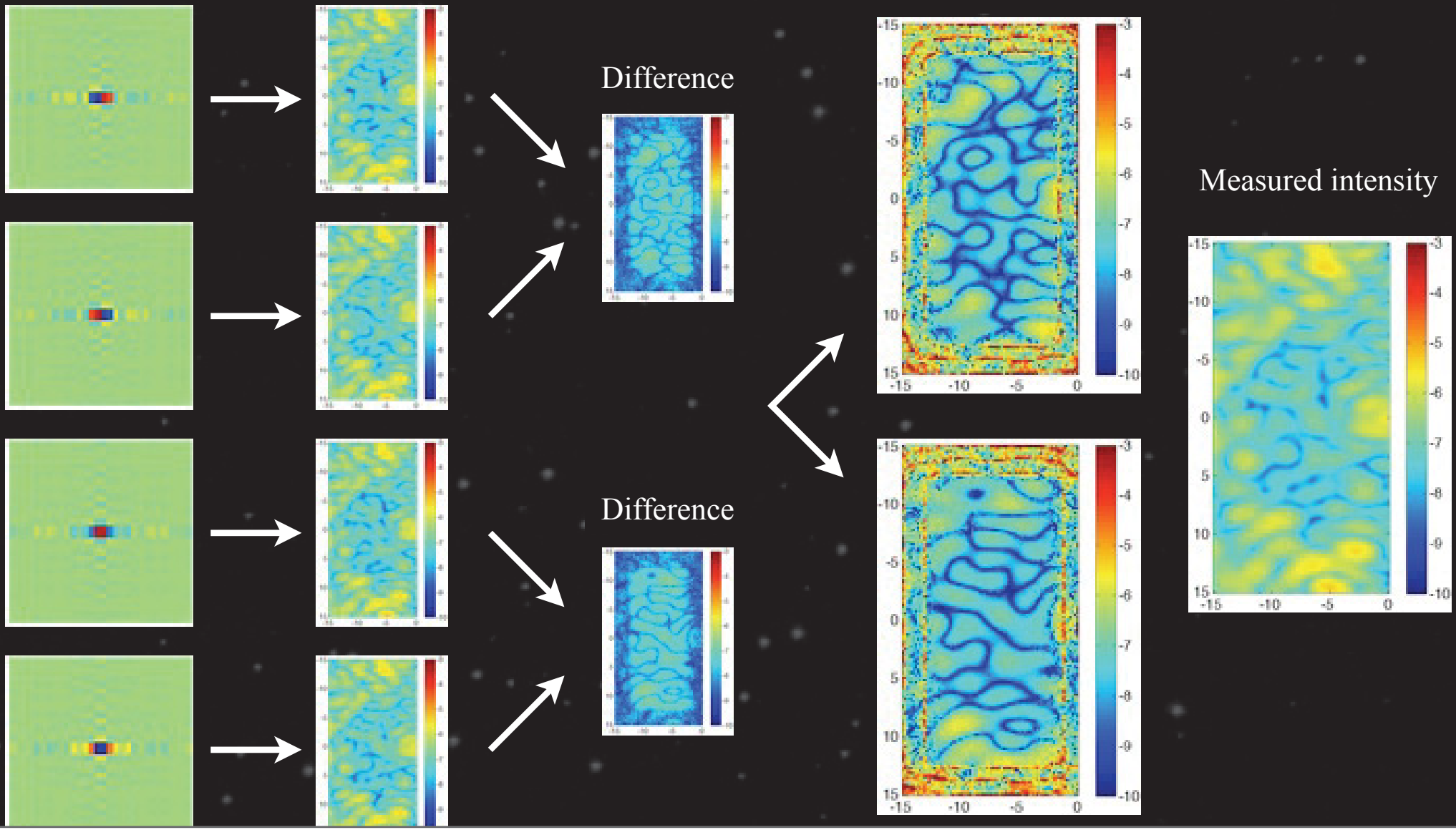
Probe images

Difference

Difference

Real and imaginary parts of the estimated Electric field

Measured intensity



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DM voltages

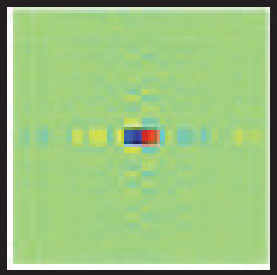
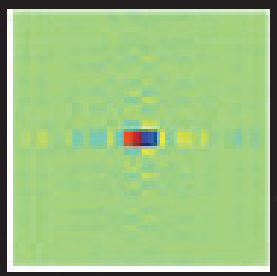
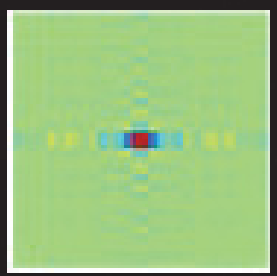
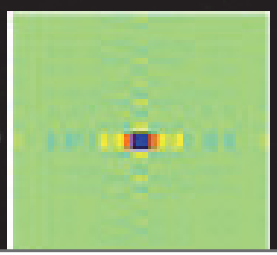
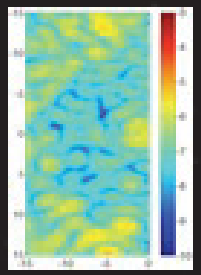
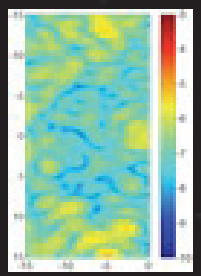
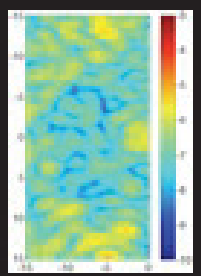
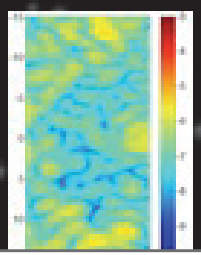
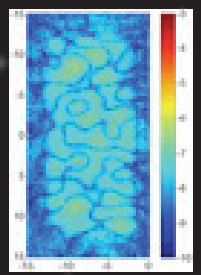
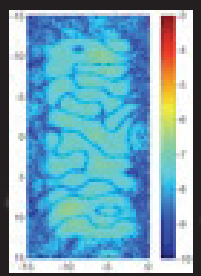
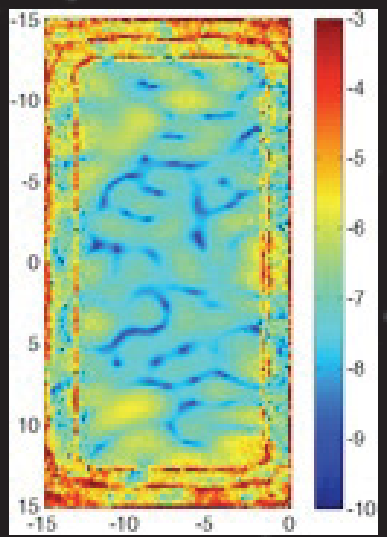
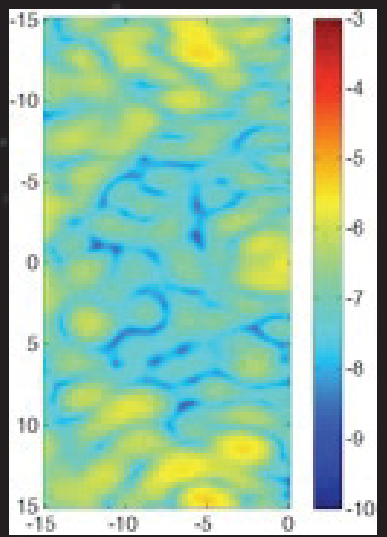
Probe images

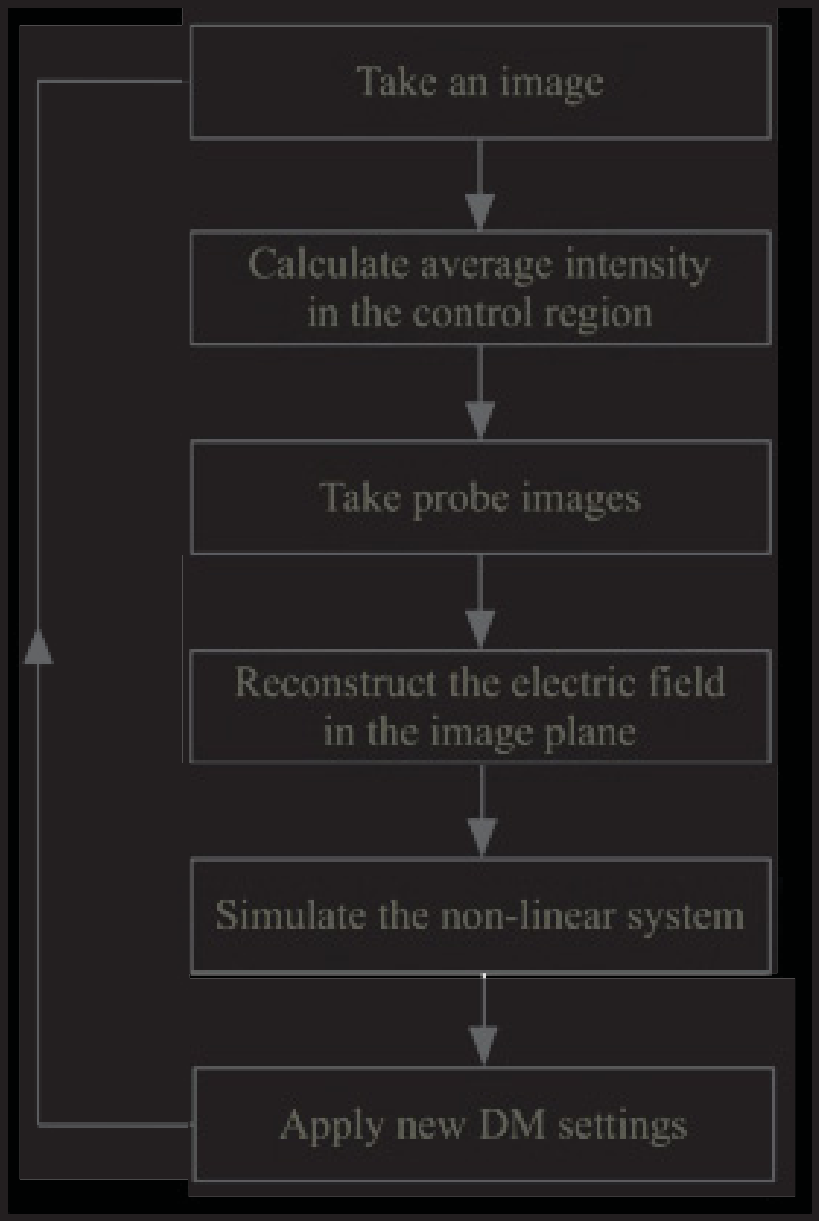
Difference

Difference

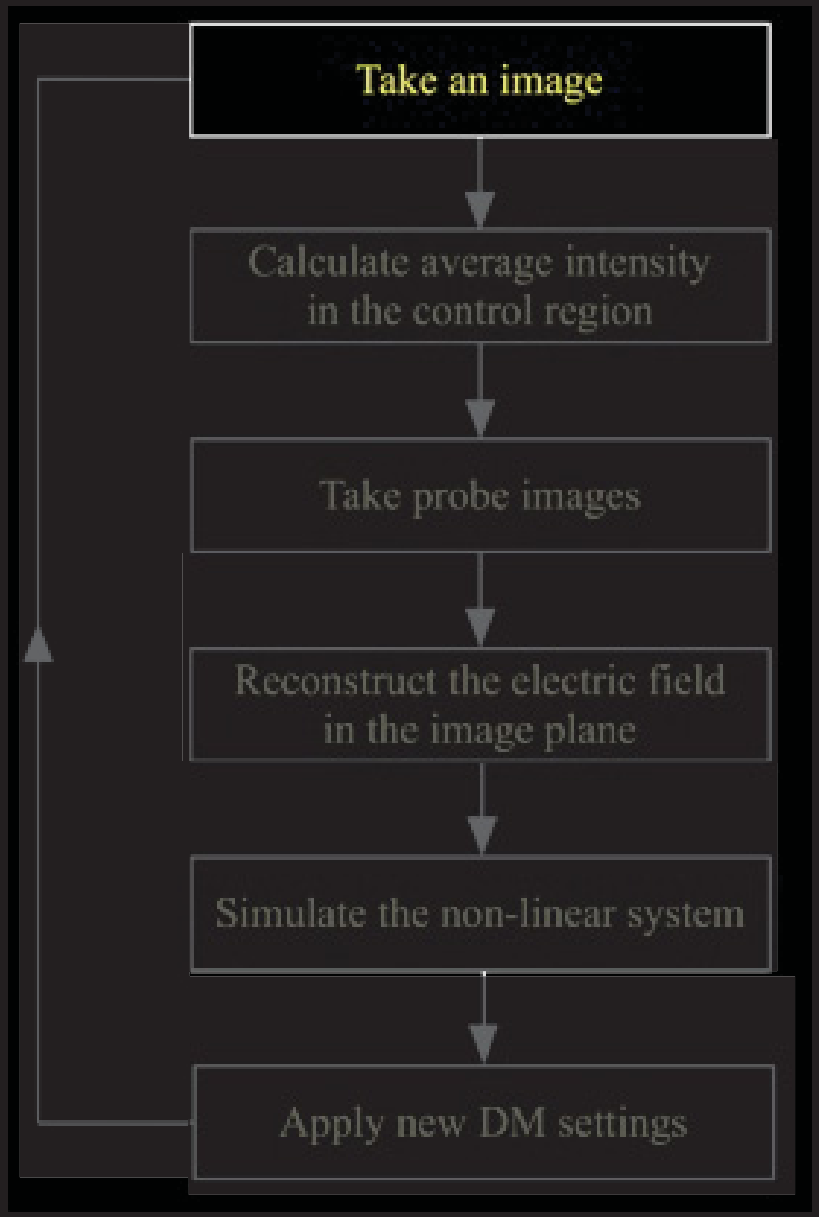
Intensity from estimated electric field

Measured intensity

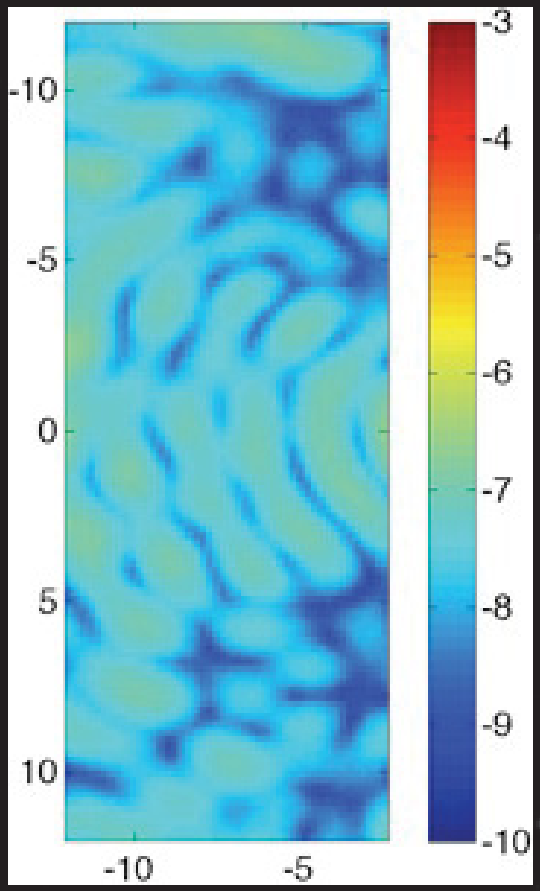














Take an image
Calculate average intensity in the control region
Take probe images
Reconstruct the electric field in the image plane
Simulate the non-linear system
Apply new DM settings

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

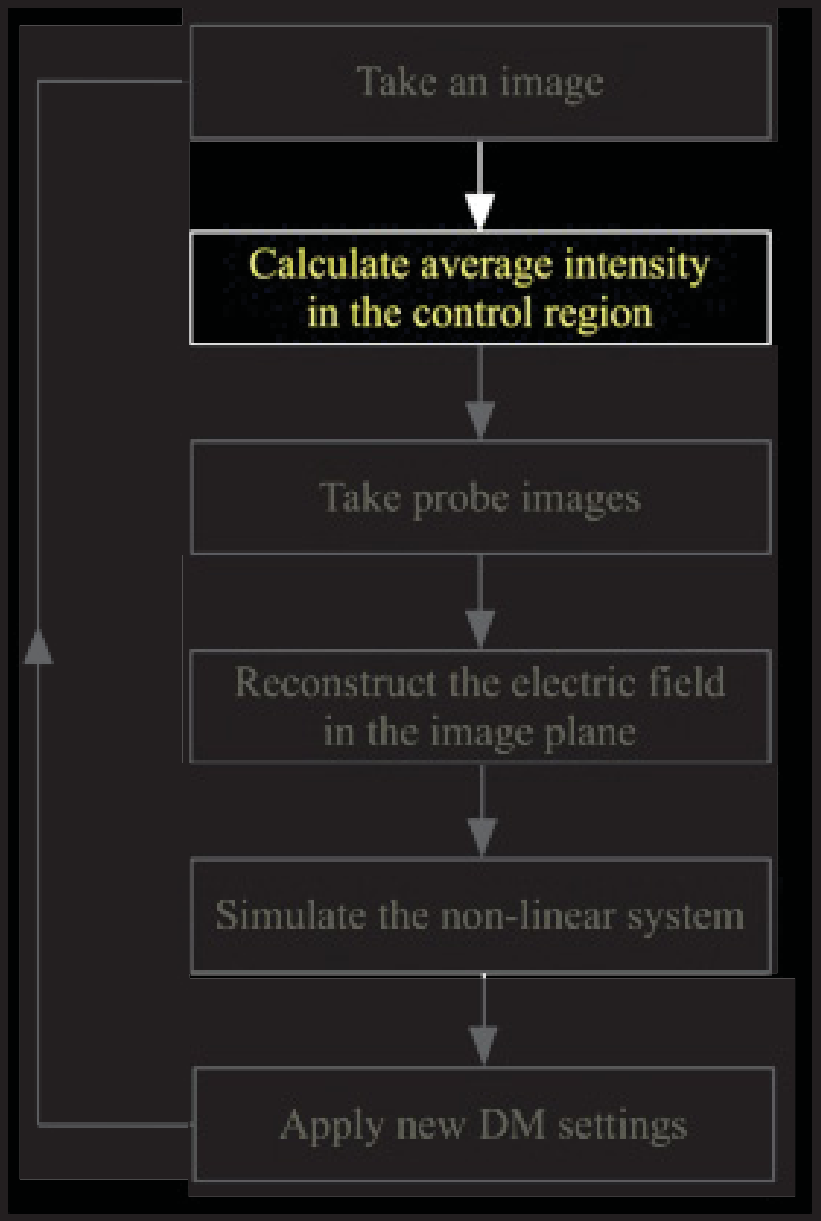


Measured image

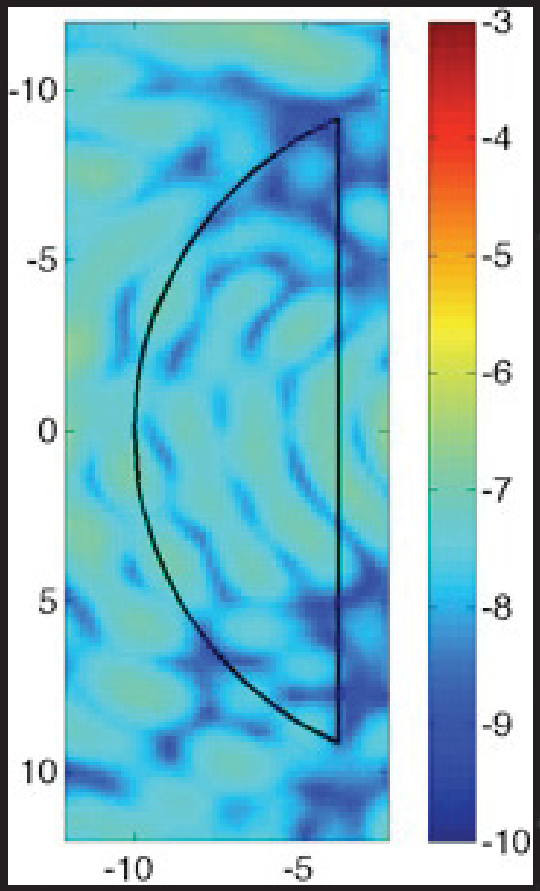


Measurements were taken at 2% around 800nm

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

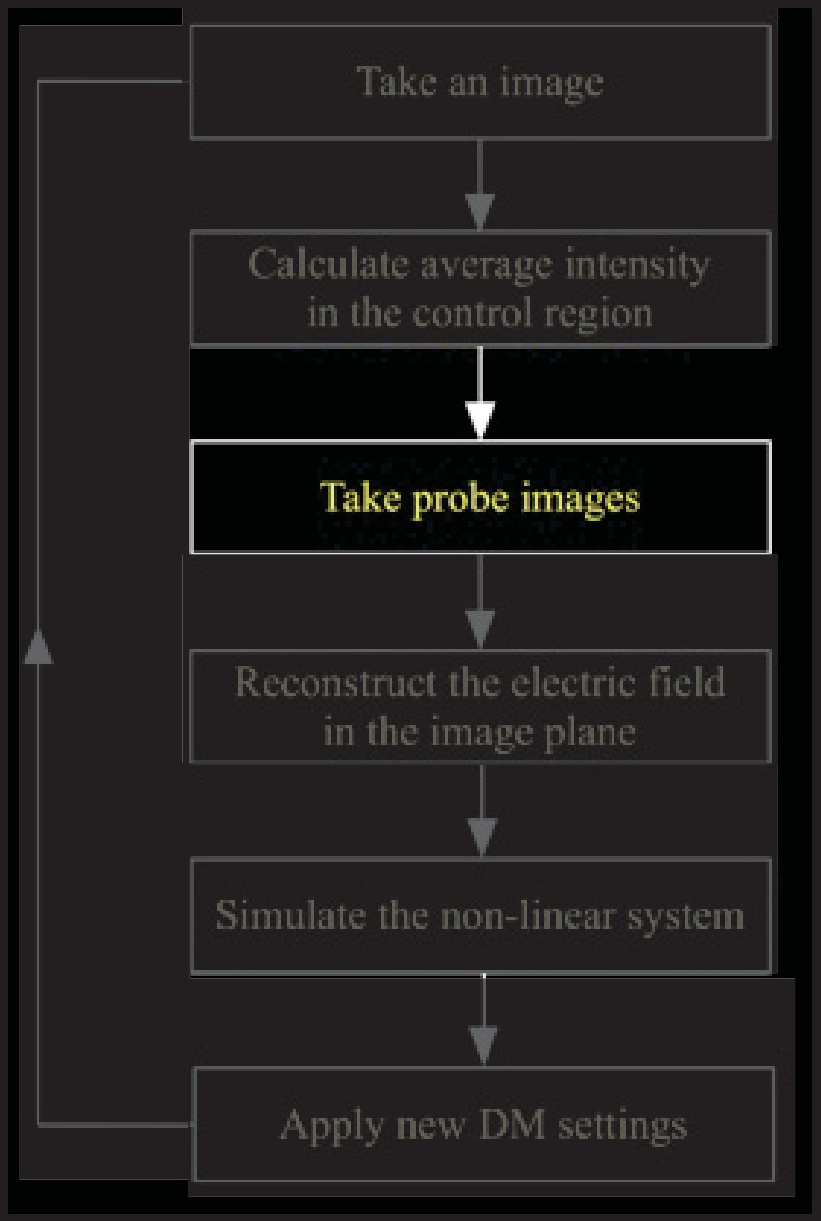


Measured image

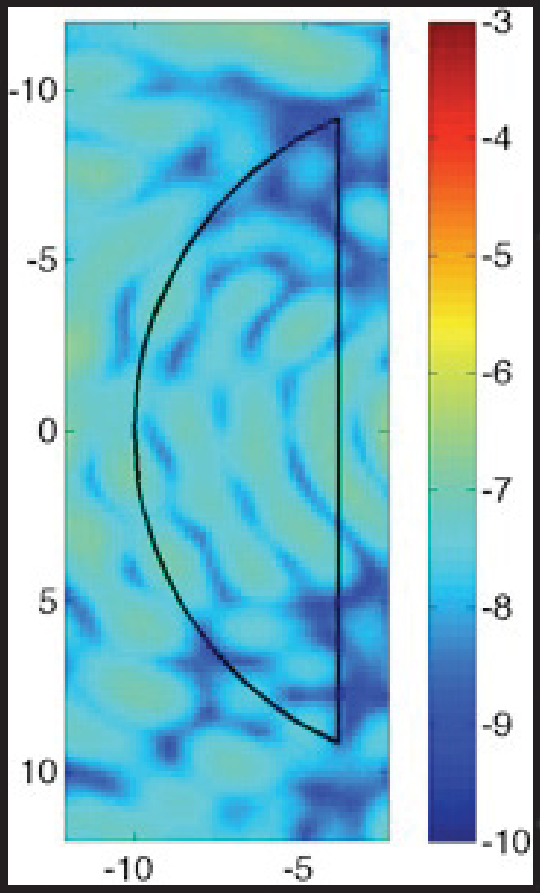


Measurements were taken at 2% around 800nm

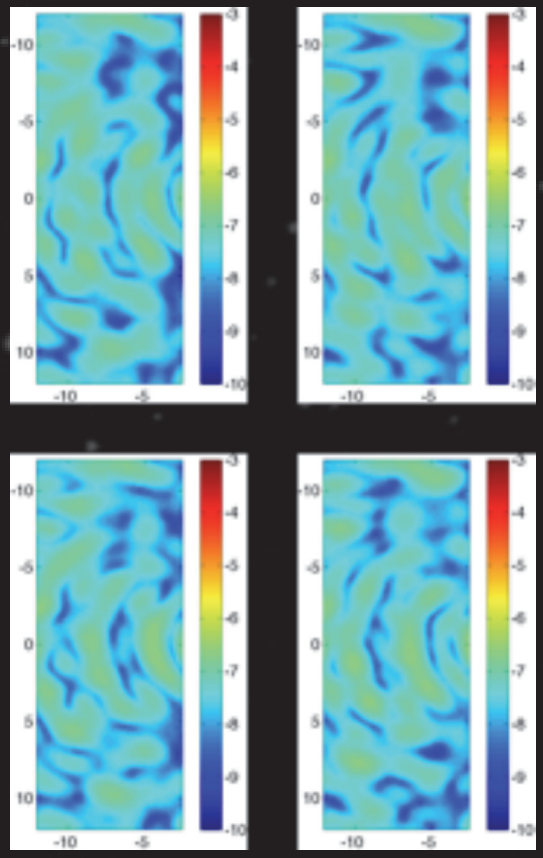
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



Measured image

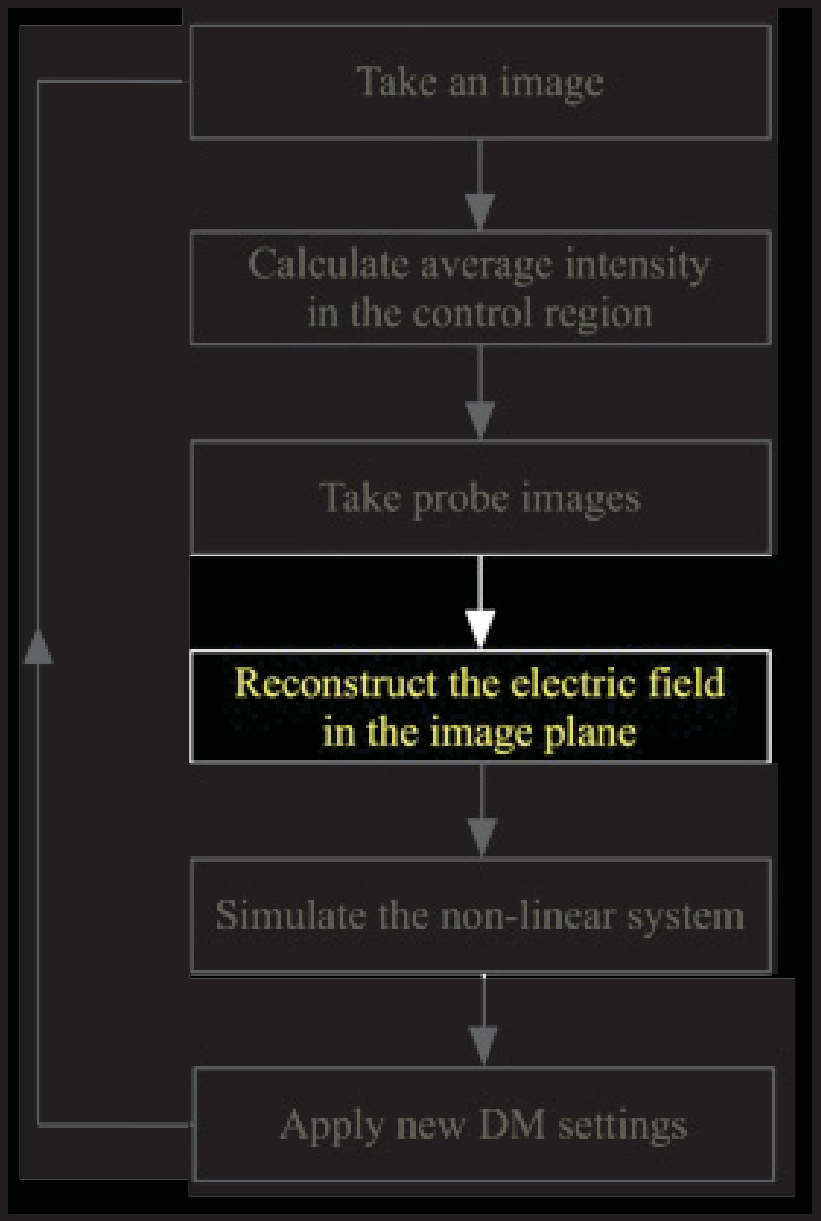


Probe images



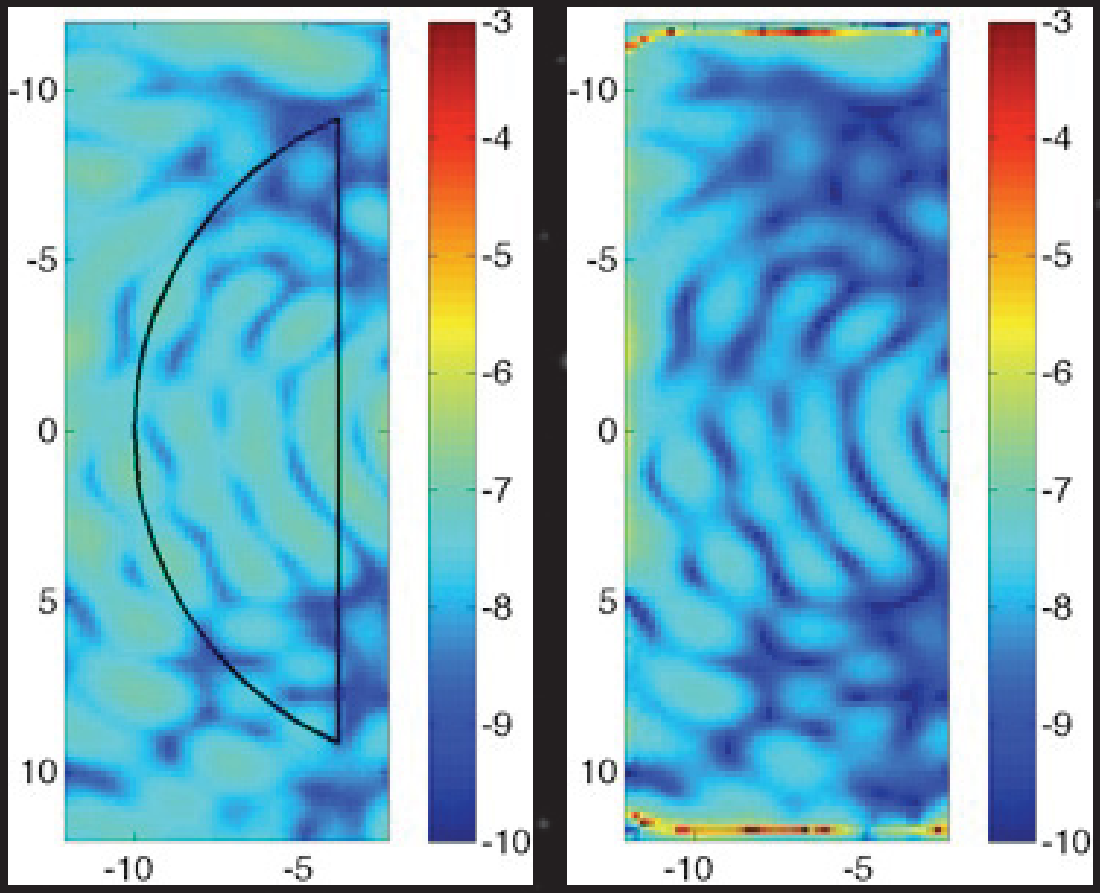
Measurements were taken at 2% around 800nm

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



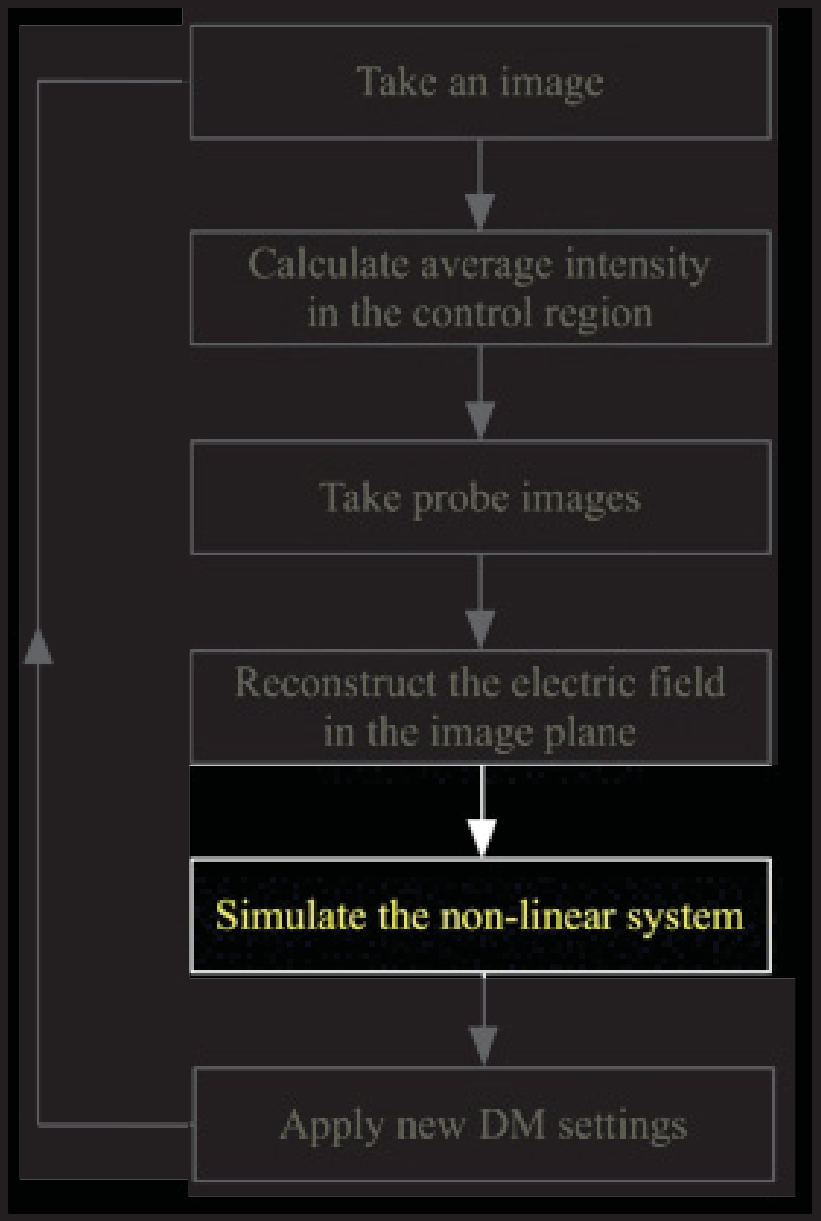
Measured image

Intensity from reconstructed electric field

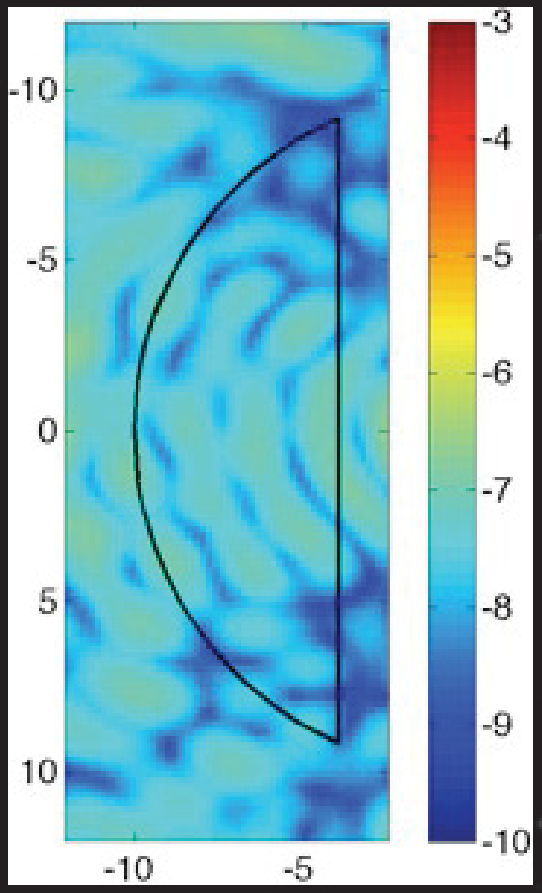


Measurements were taken at 2% around 800nm

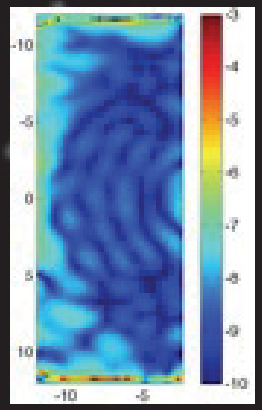
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



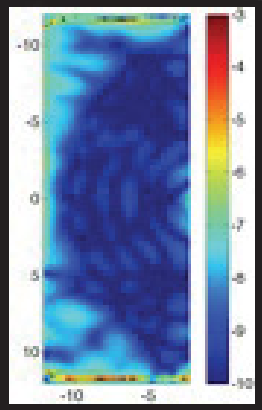
Measured image



After one iteration

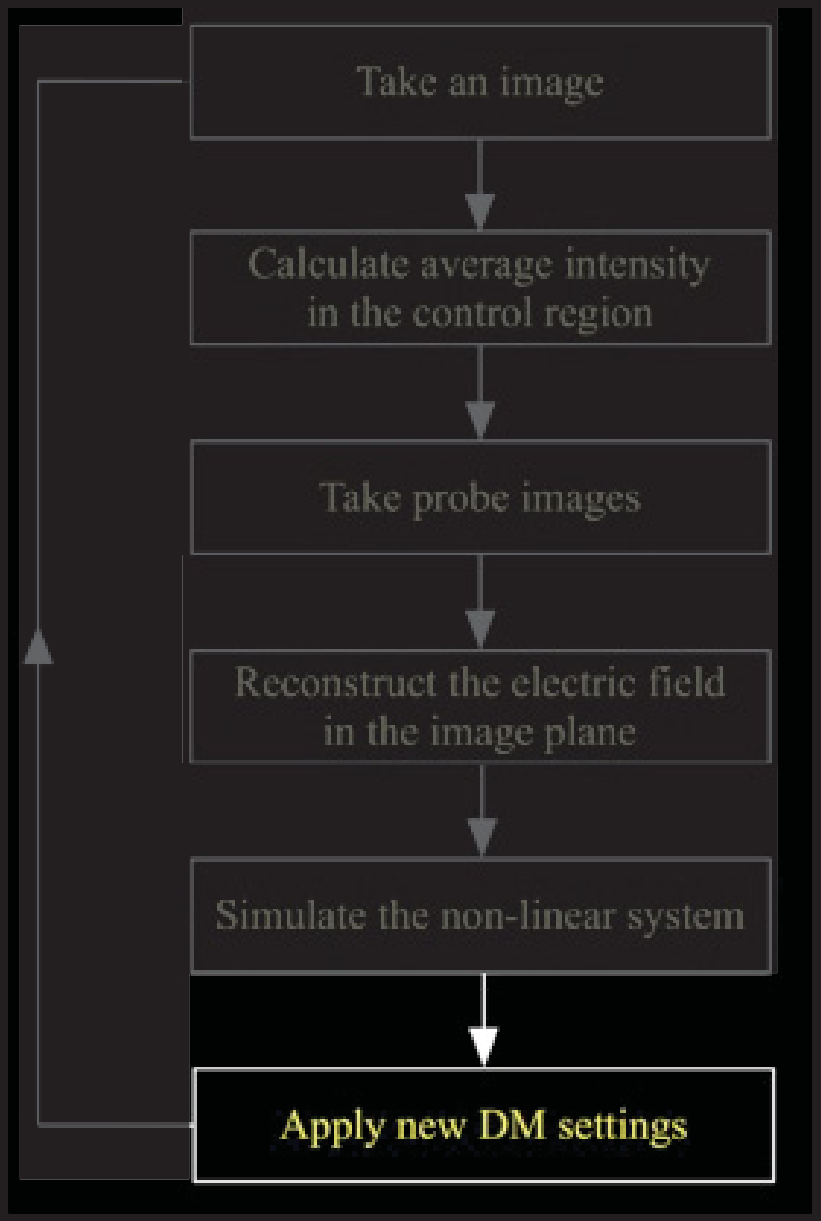


After five non-linear analytic sub-steps

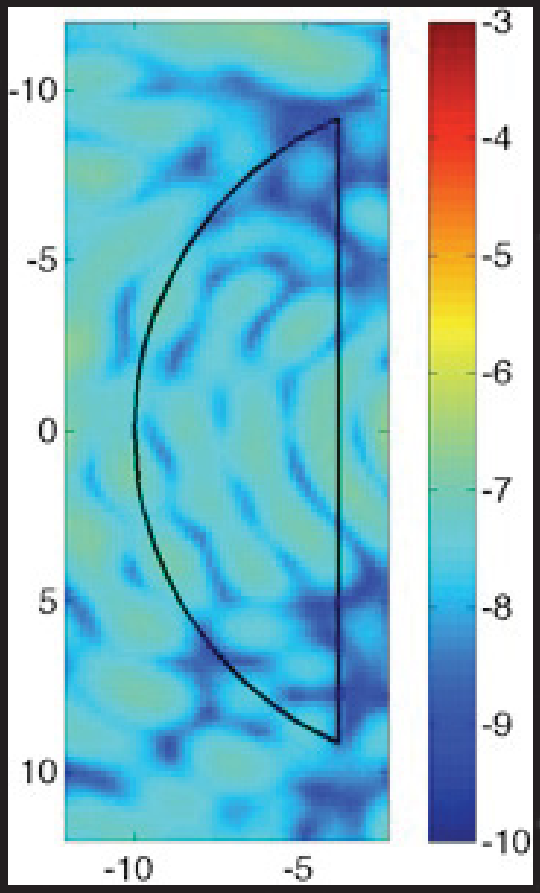


Measurements were taken at 2% around 800nm

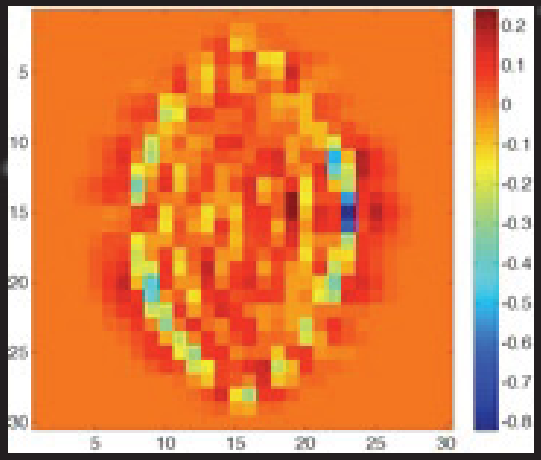
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



Measured image

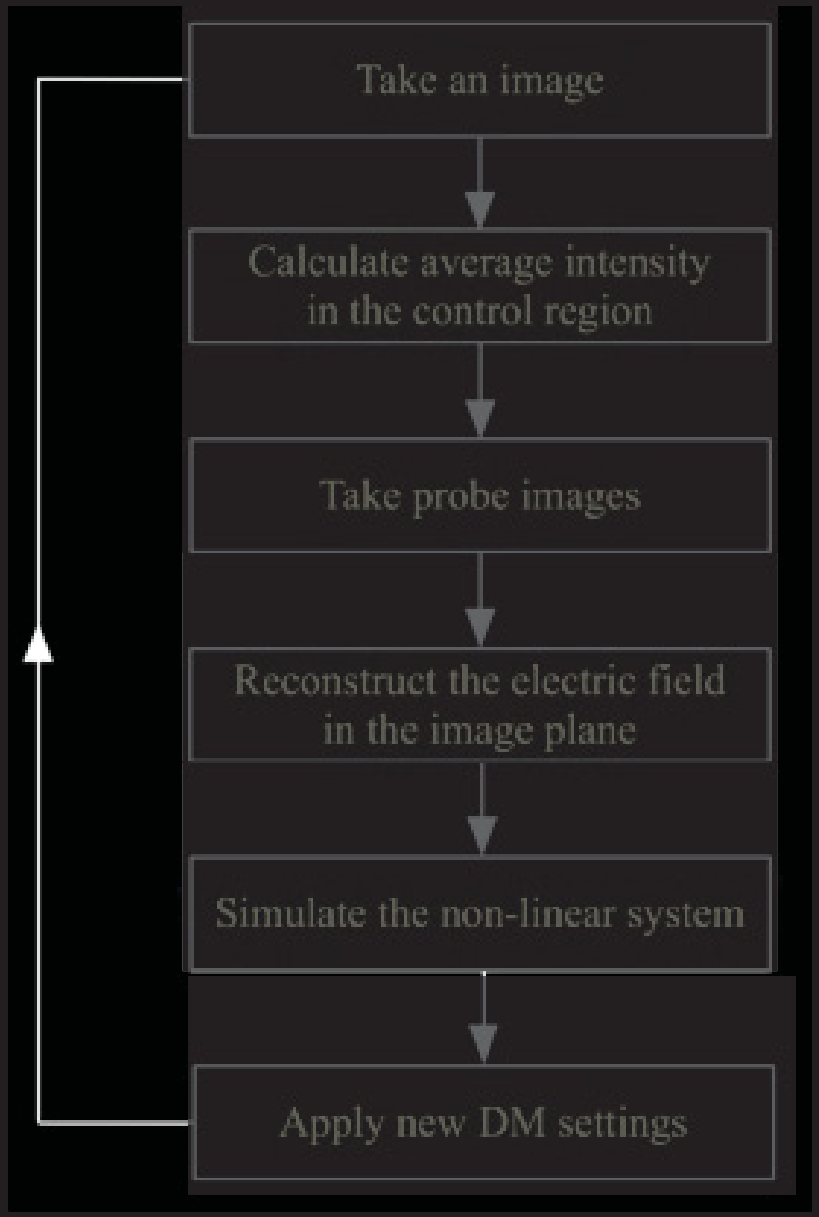


Change in DM actuators

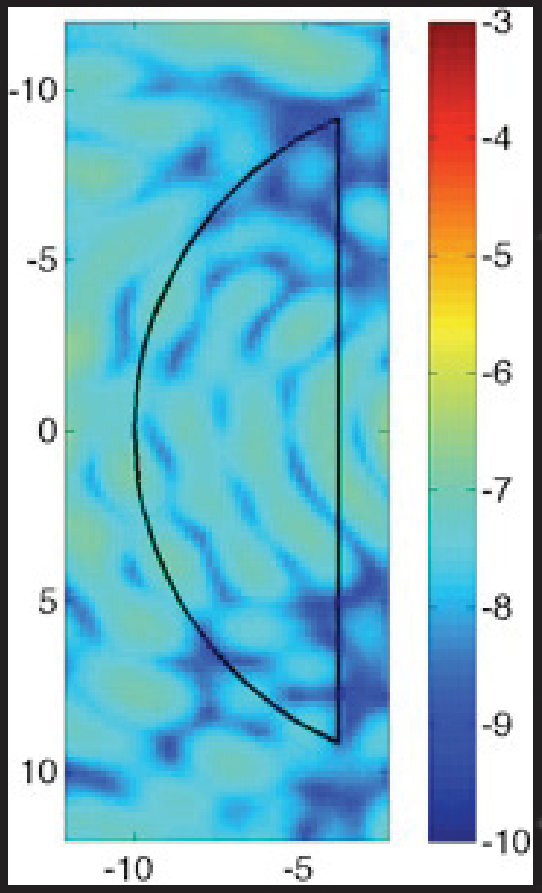


Measurements were taken at 2% around 800nm

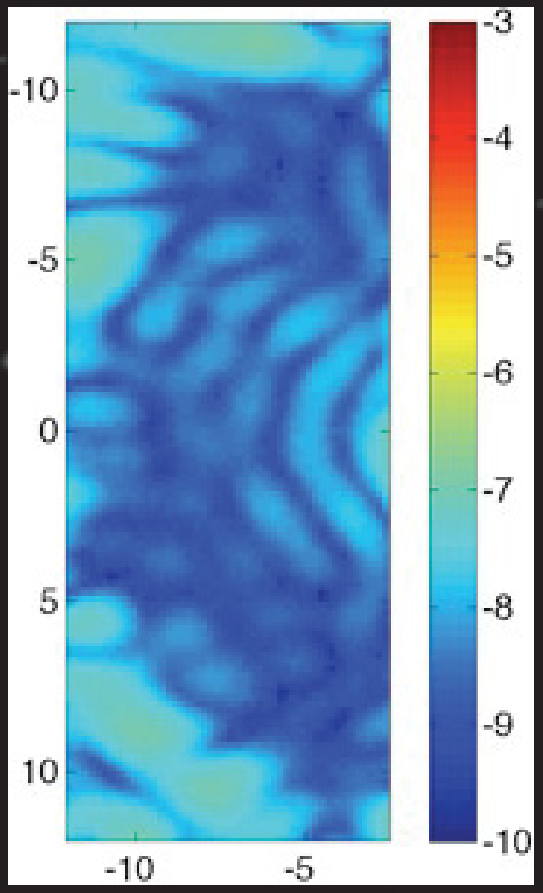
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



Measured image



New measured image

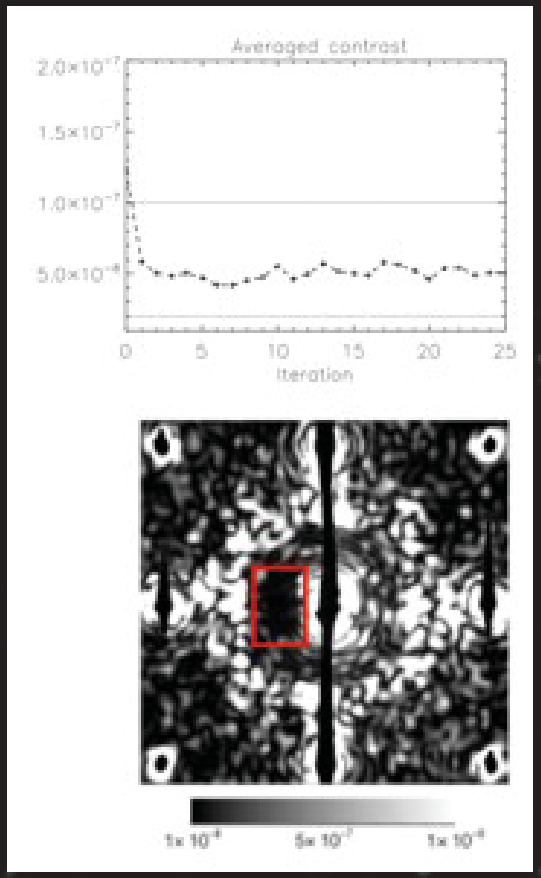


Measurements were taken at 2% around 800nm

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

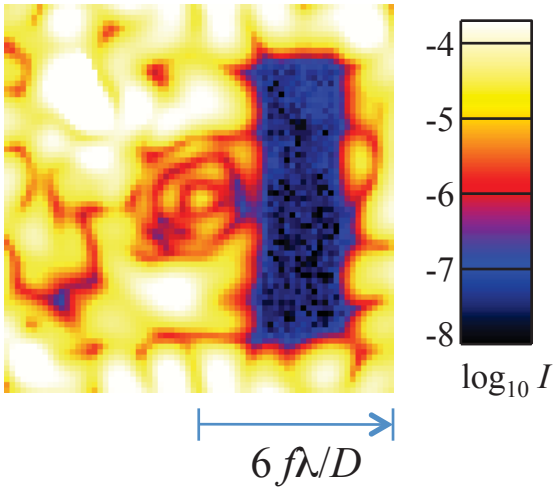
Results in various labs

Laboratory for Adaptive Optics
UC Santa-Cruz



Give'on et al 2008, Thomas et al 2010

High Contrast Imaging Testbed
Jet Propulsion Laboratory

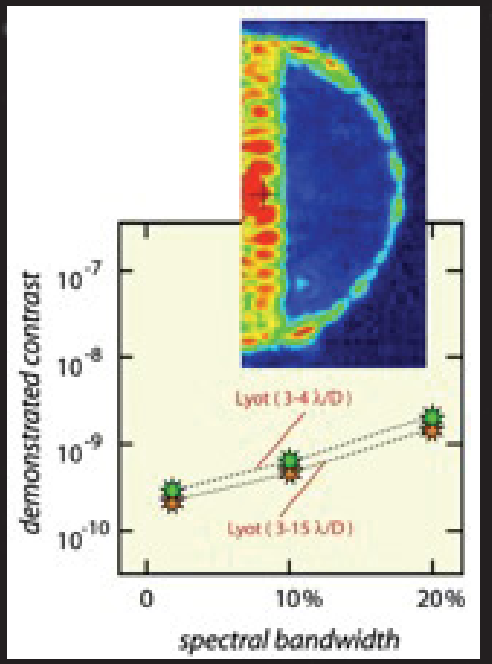


Best dark hole to date has mean intensity 3.5×10^{-8}

Region is $2 < x / (f\lambda/D)_{sky} < 4$, $-4 < y / (f\lambda/D)_{sky} < 4$

Inner edge of dark hole 2.05 $(f\lambda/D)_{sky}$

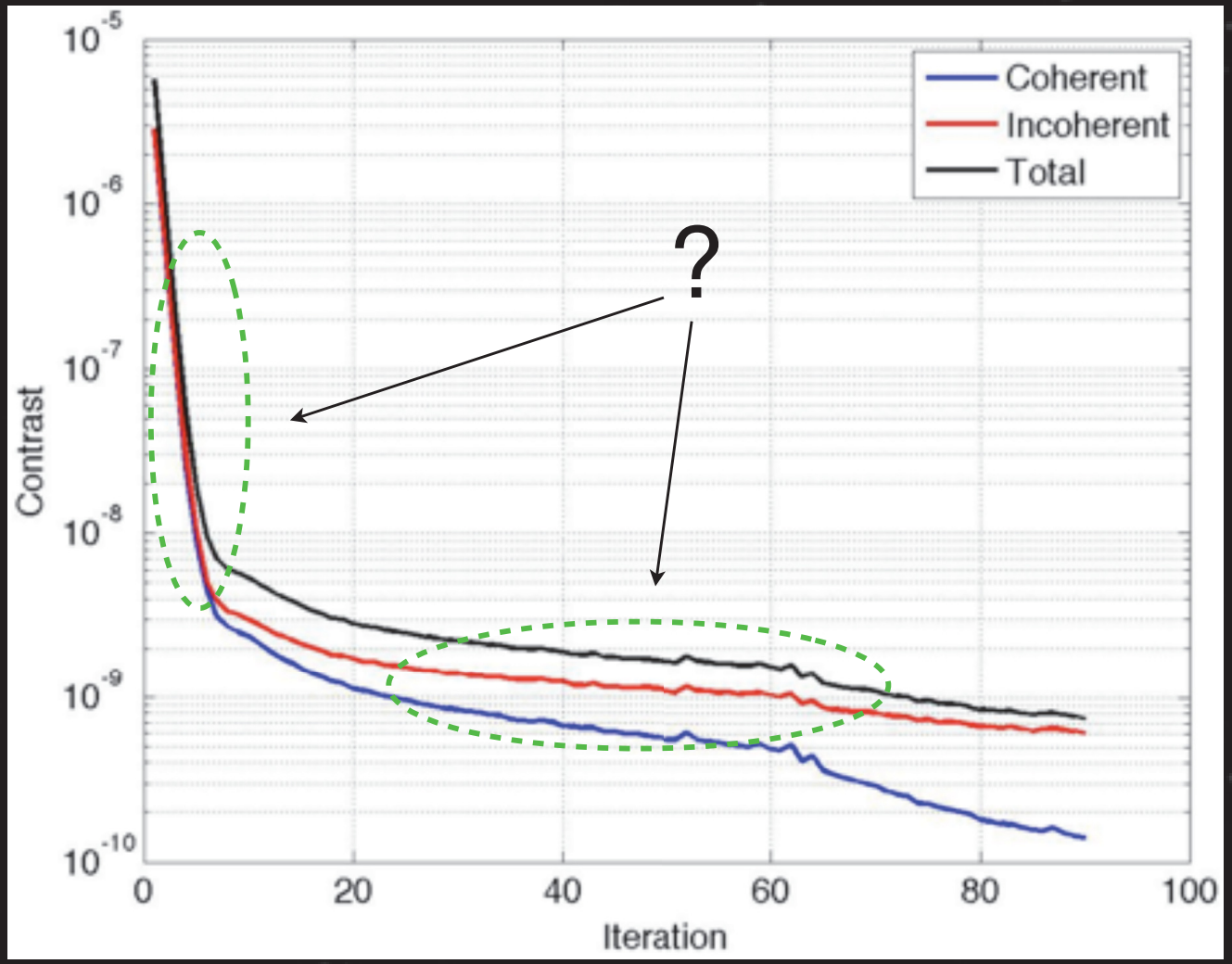
Kern et al SPIE 8151, 2011



Trauger et al SPIE 8151, 2011

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Incoherent? or Uncontrollable? or?...

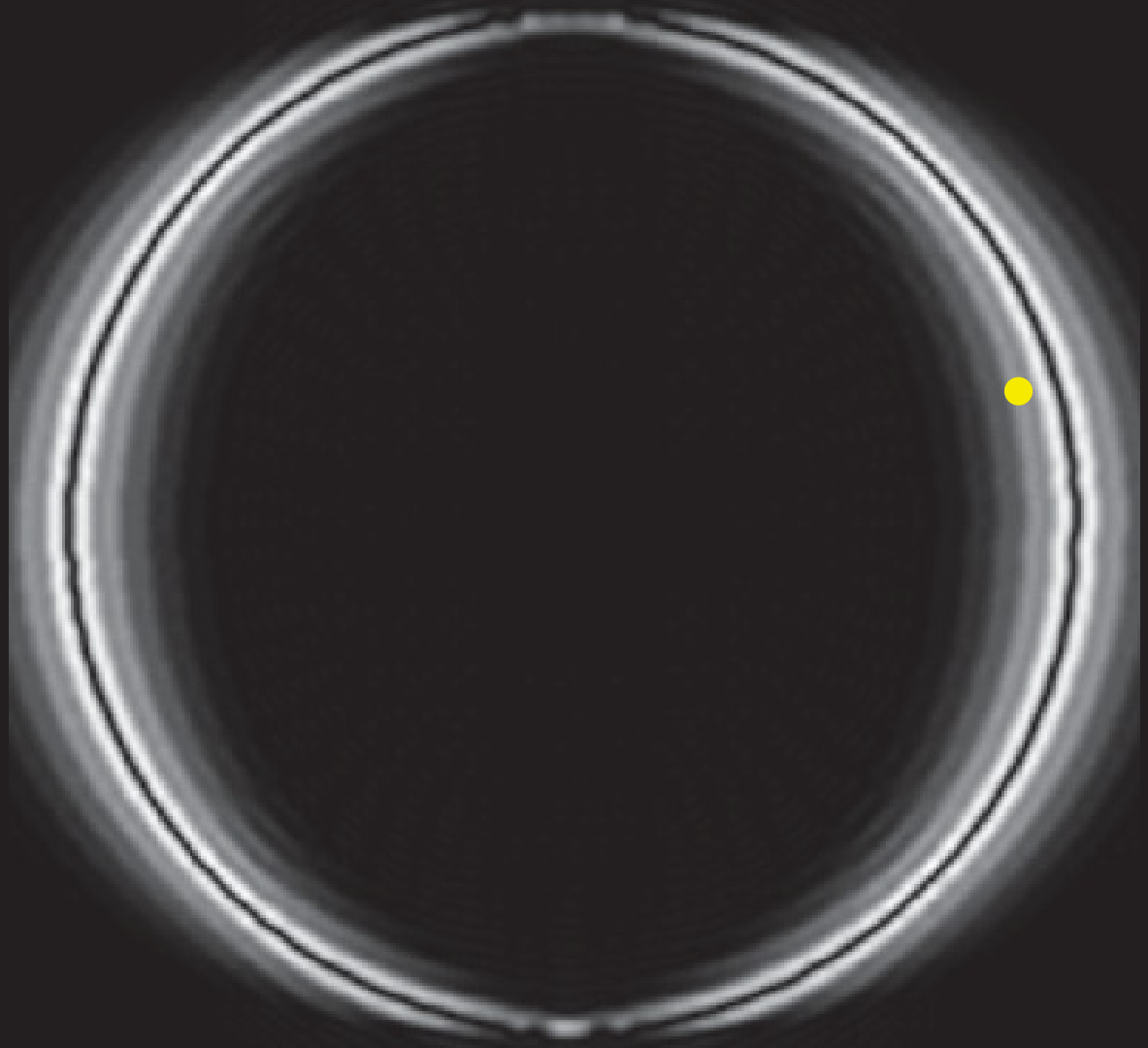


This can be due to inability to resolve changes over time, space or polarization (in between exposures of the probes.

However, this can also be due to errors in the model of the system (probes).

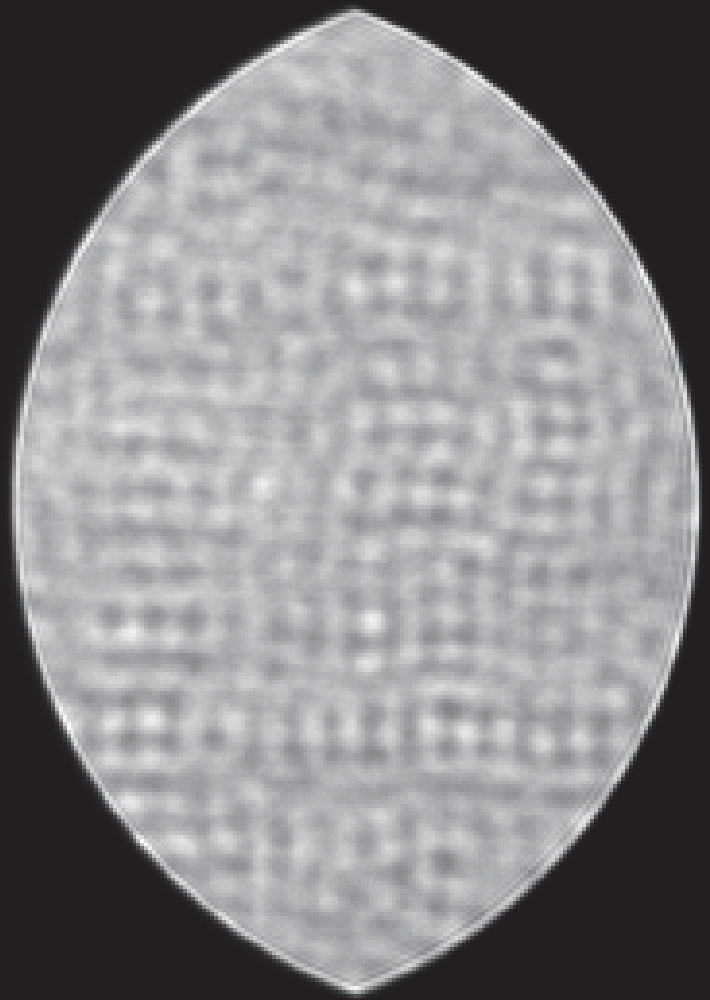
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Light in the Lyot plane



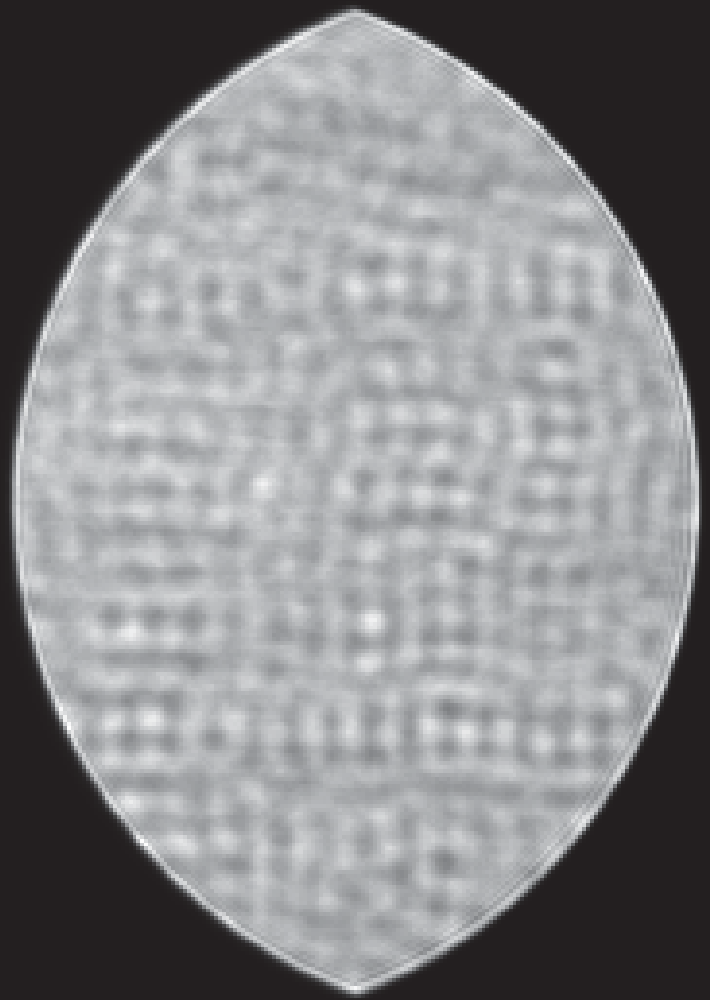
The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time



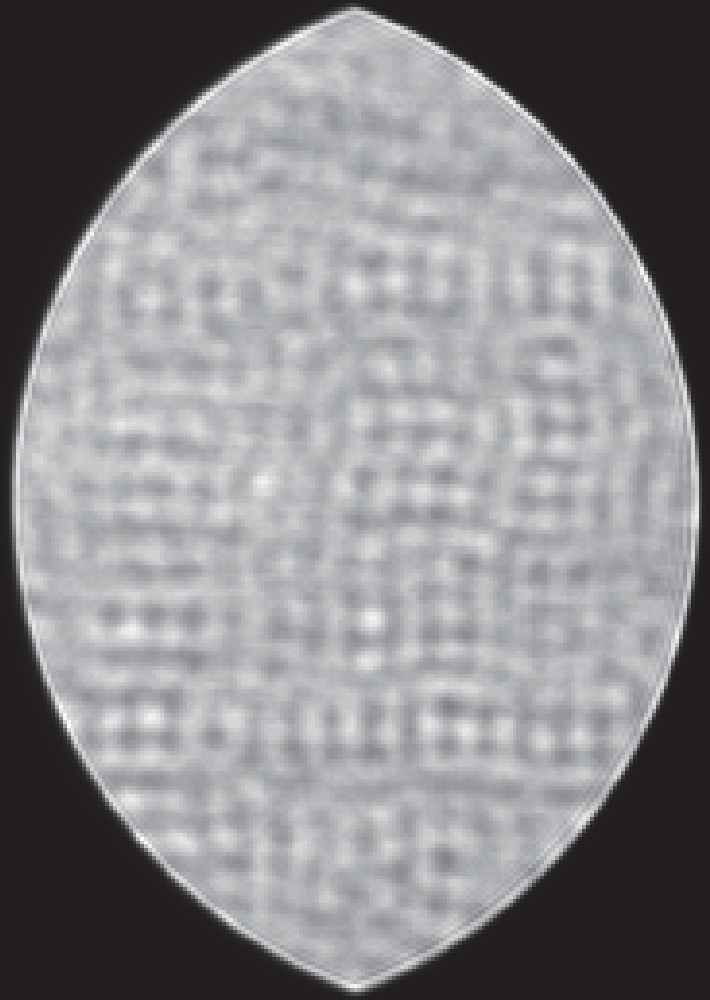
The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time



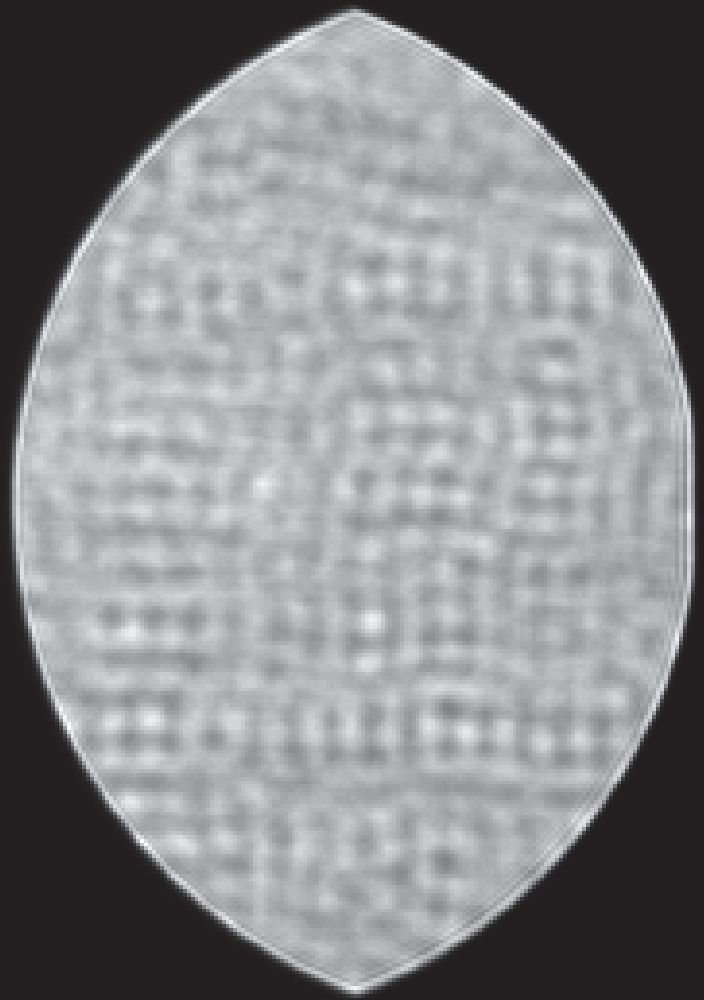
The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time



The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time

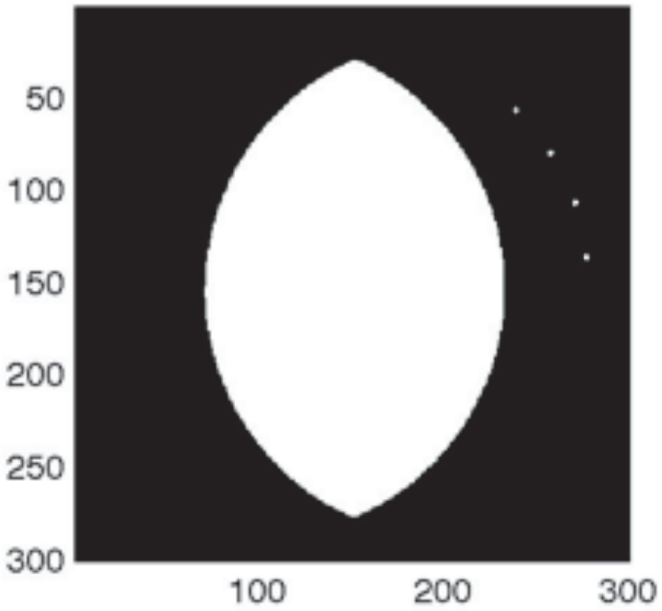


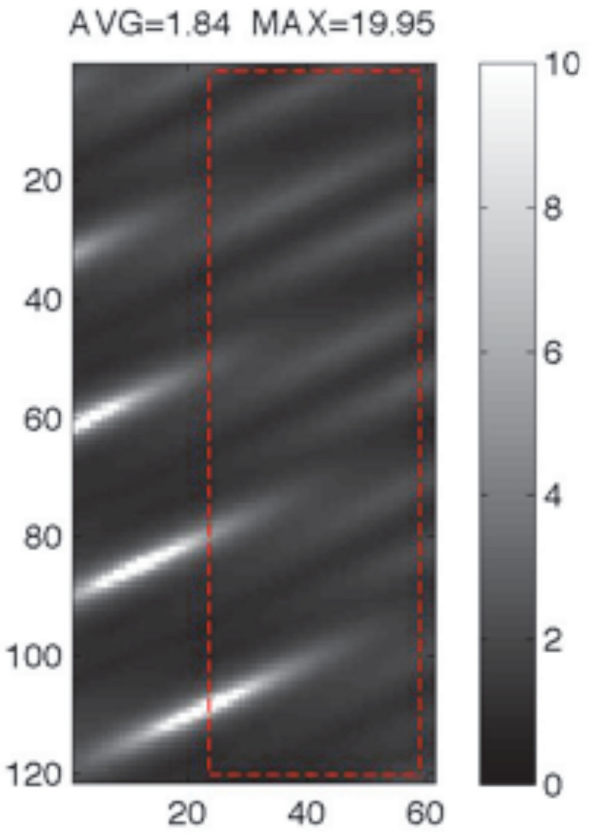
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Choosing the locations of the pinholes

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Choosing the locations of the pinholes

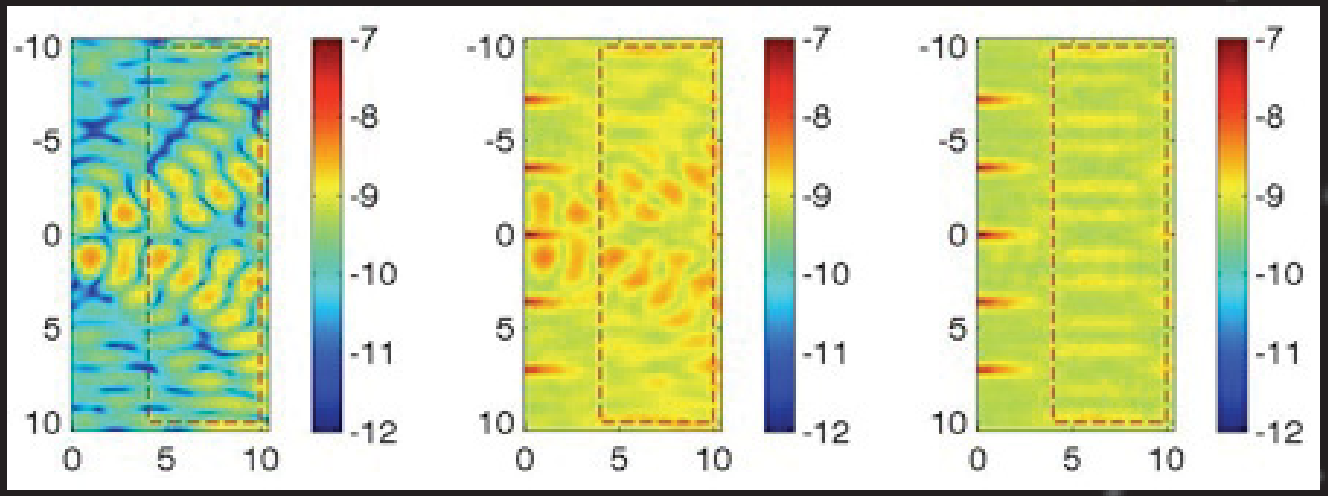




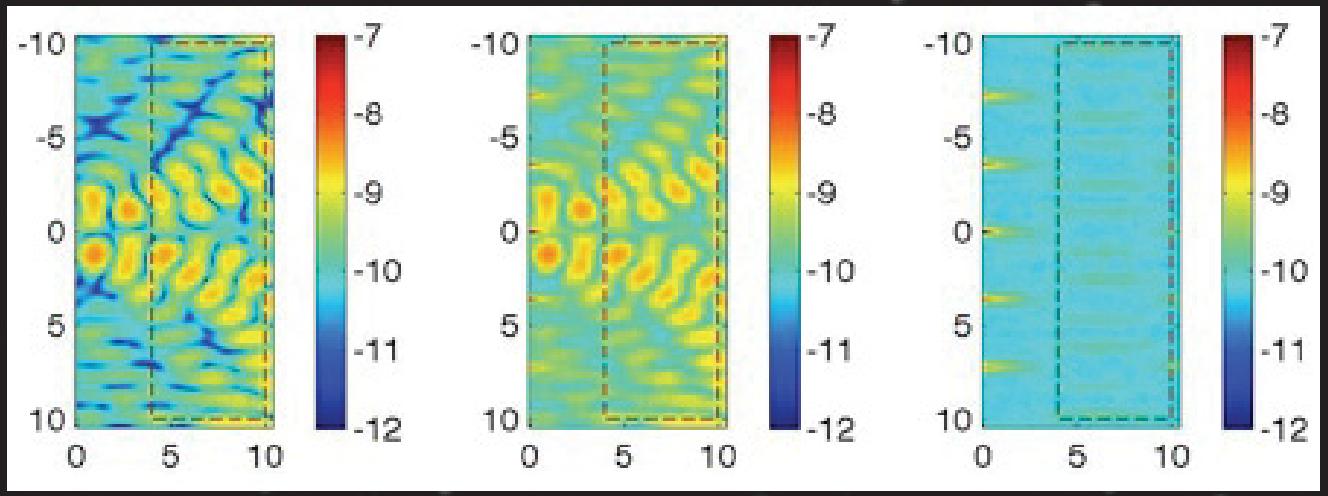
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

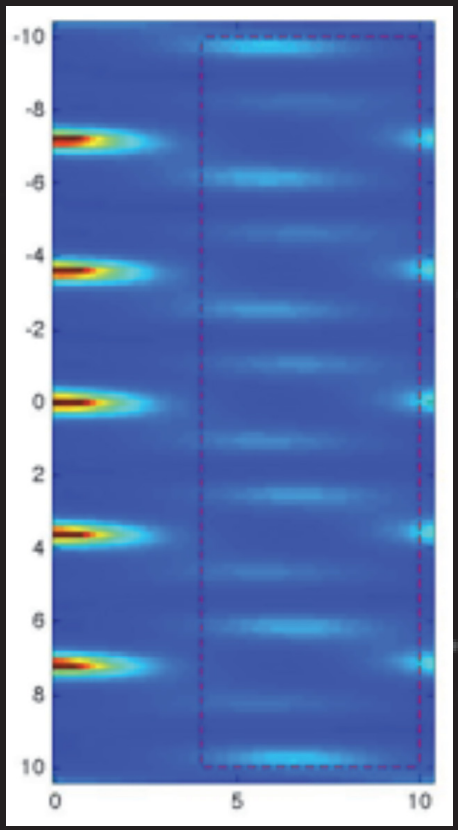
Simulations with photon noise

1 Photon per 1e-8 contrast



1 Photon per 1e-9 contrast

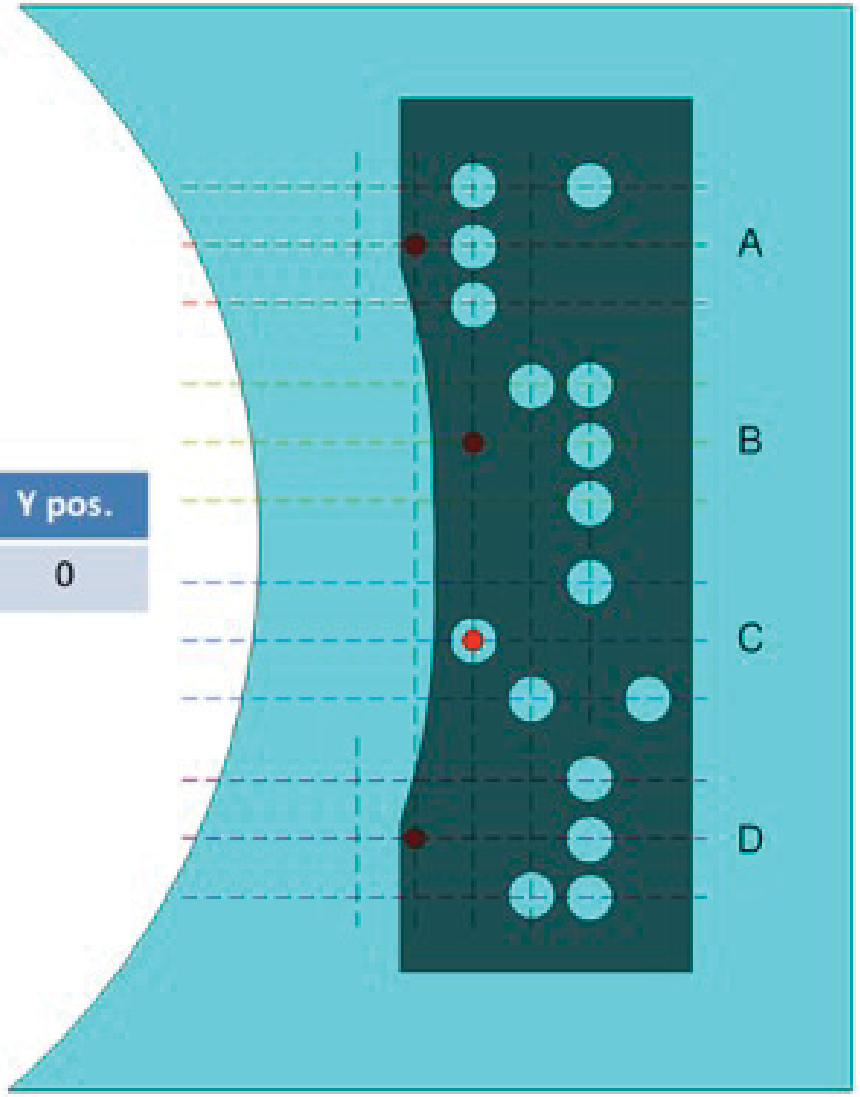


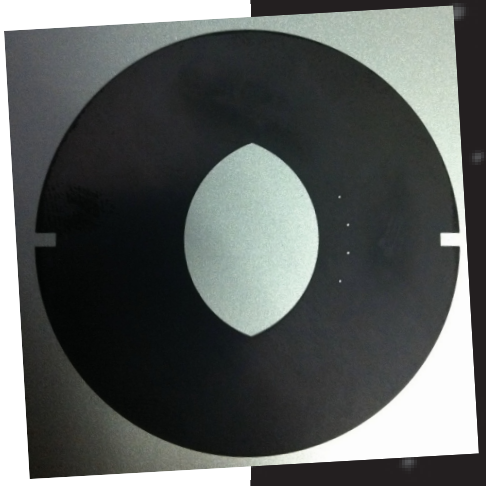


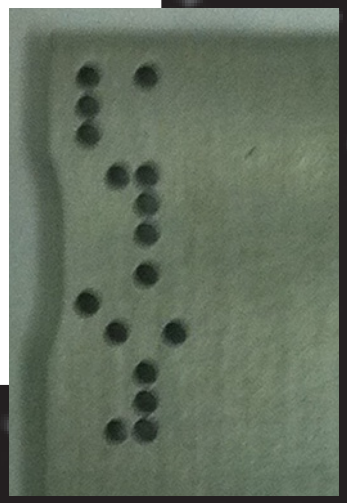
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes

State	X pos.	Y pos.
1	0	0



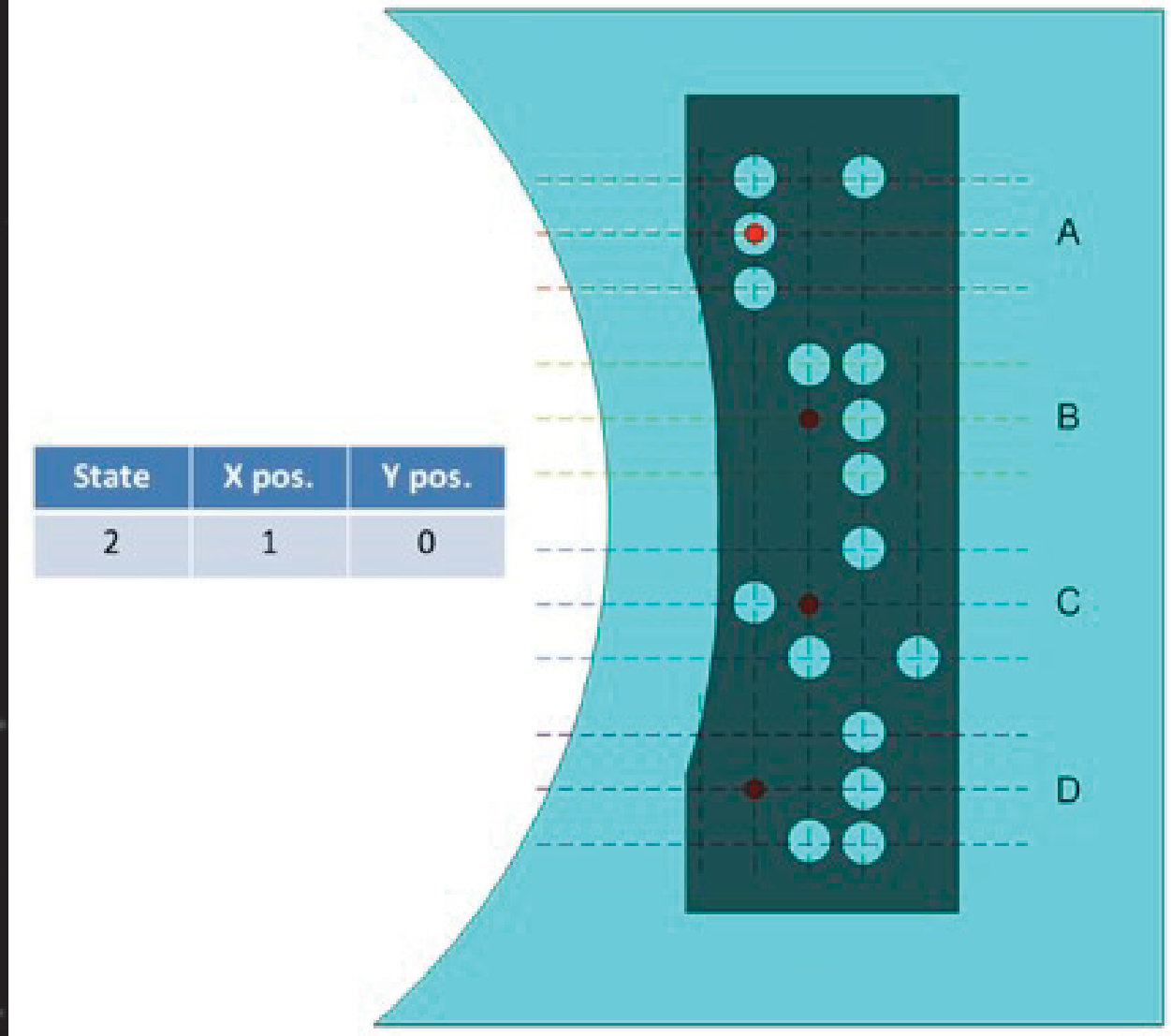


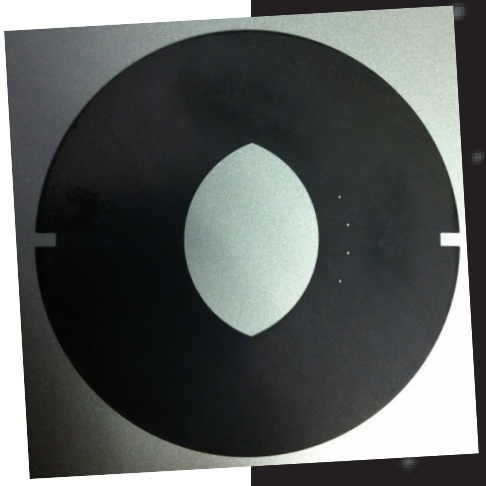


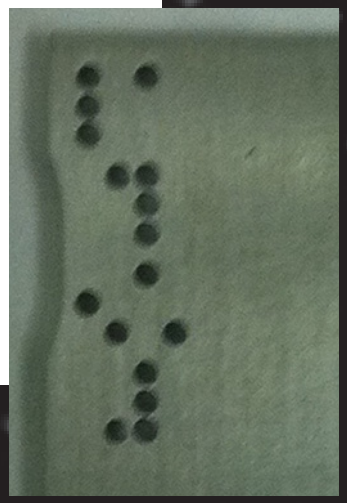
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes

State	X pos.	Y pos.
2	1	0



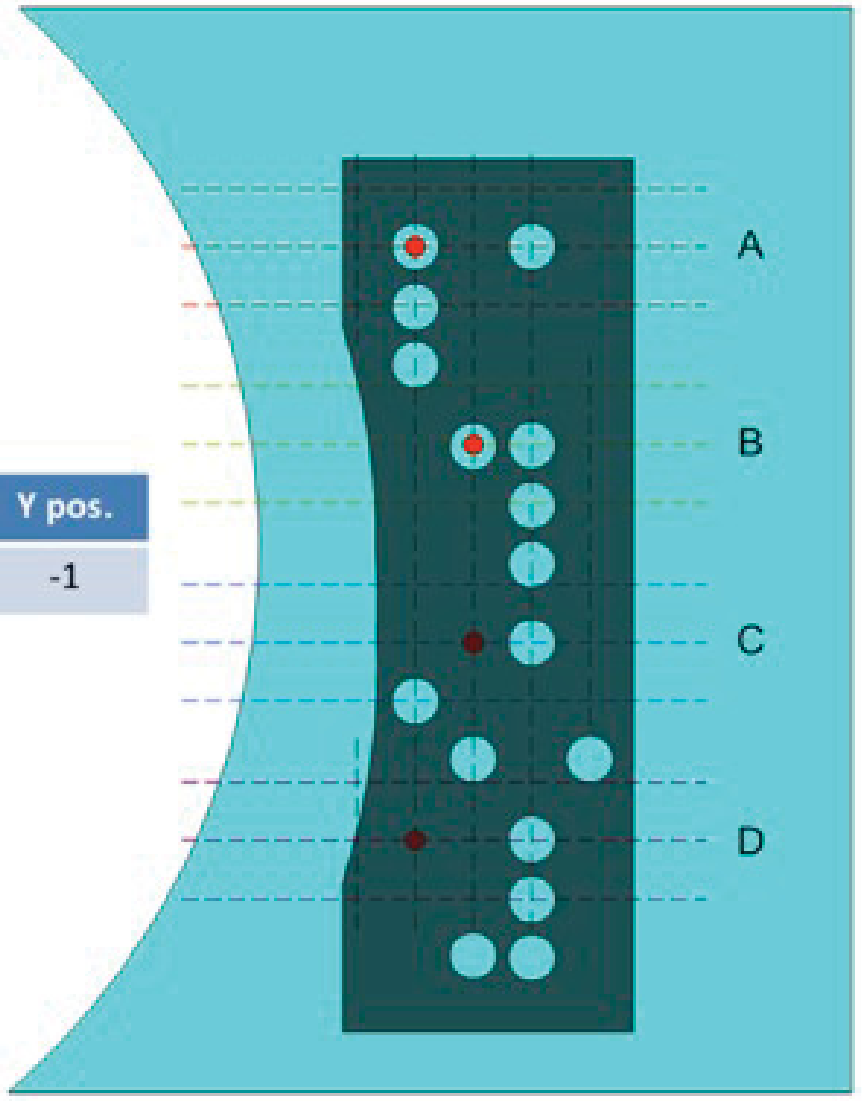


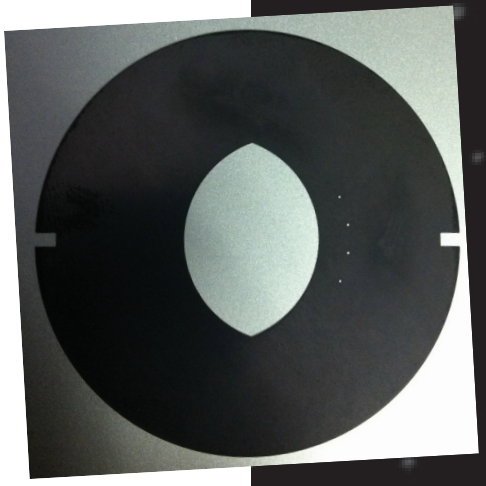


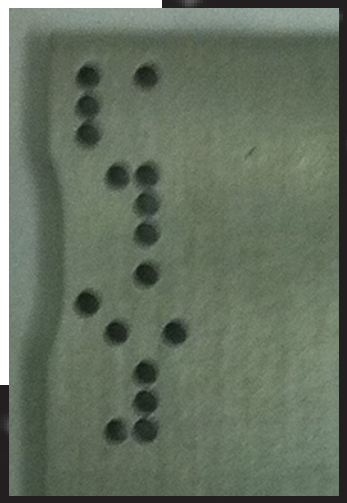
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes

State	X pos.	Y pos.
3	1	-1



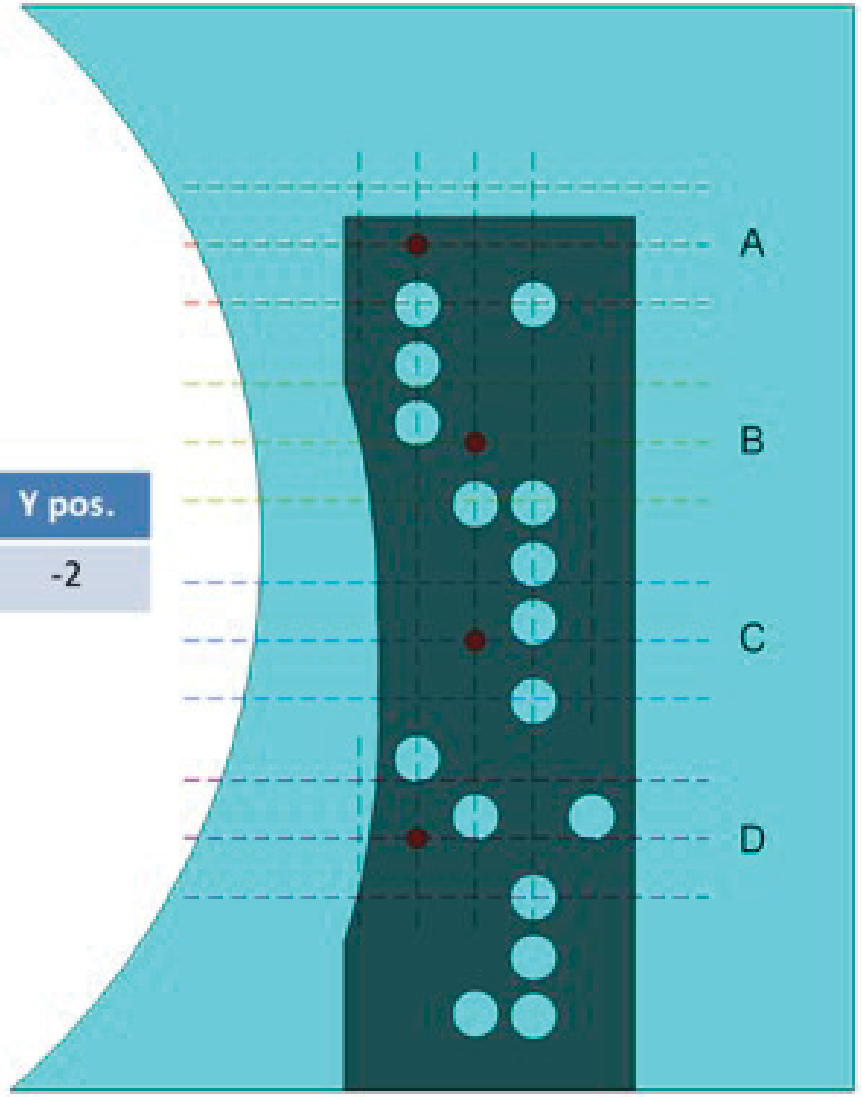


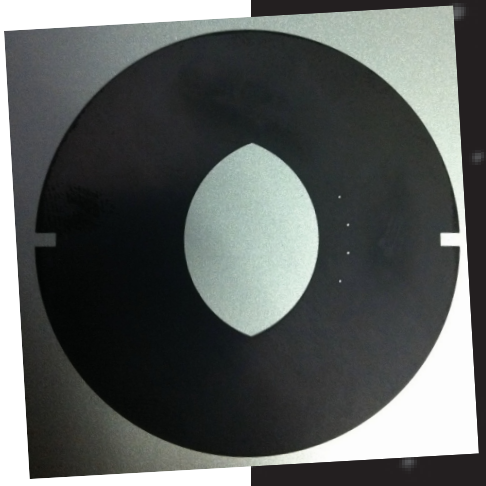


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes

State	X pos.	Y pos.
4	1	-2

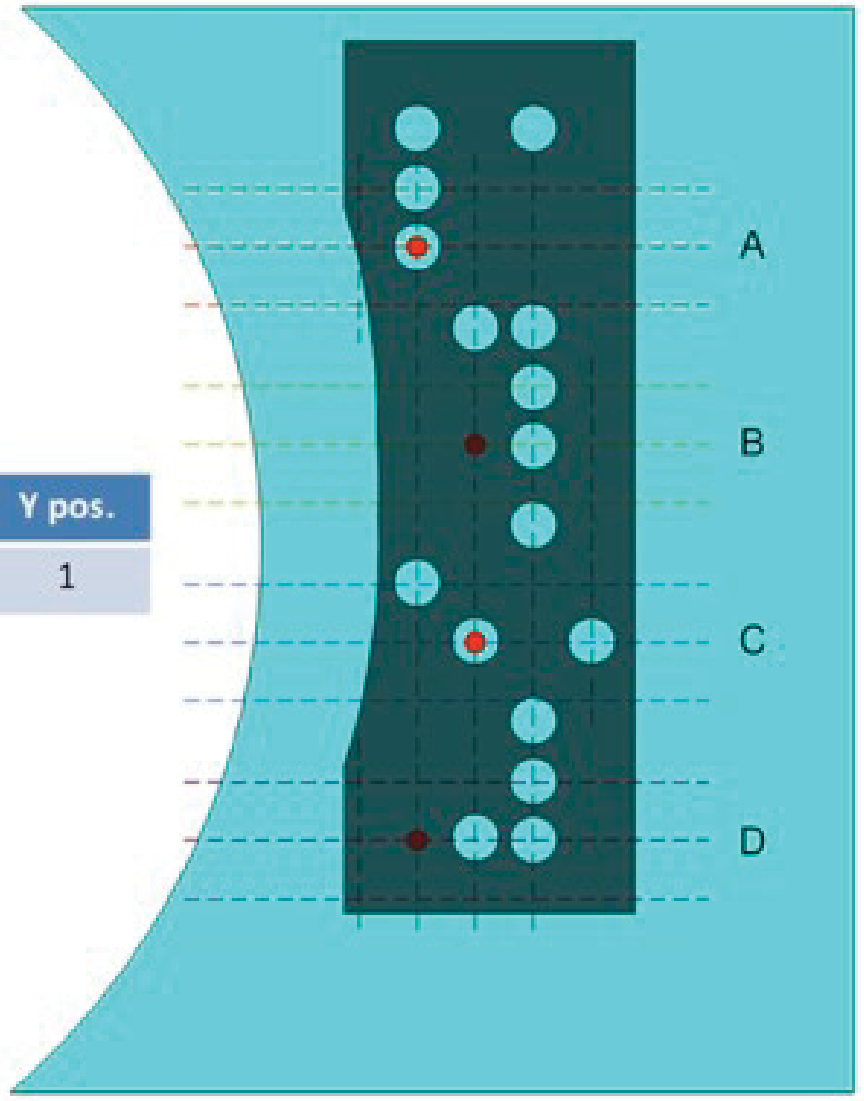


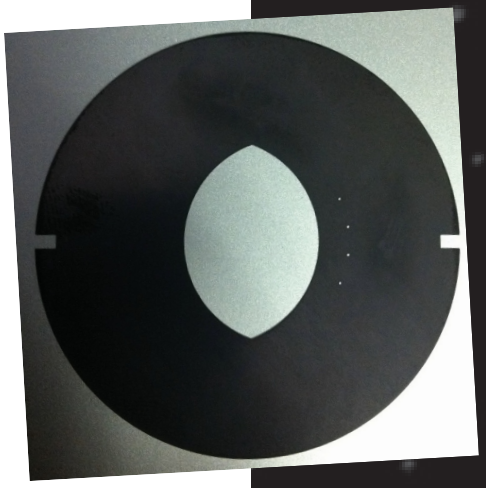


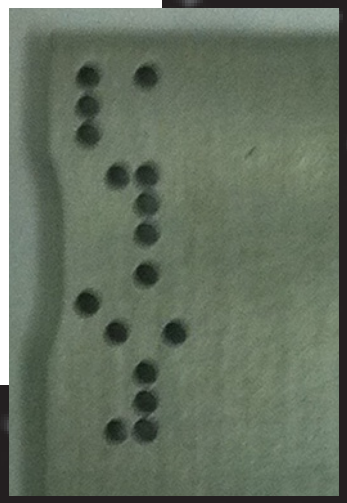
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes

State	X pos.	Y pos.
5	1	1

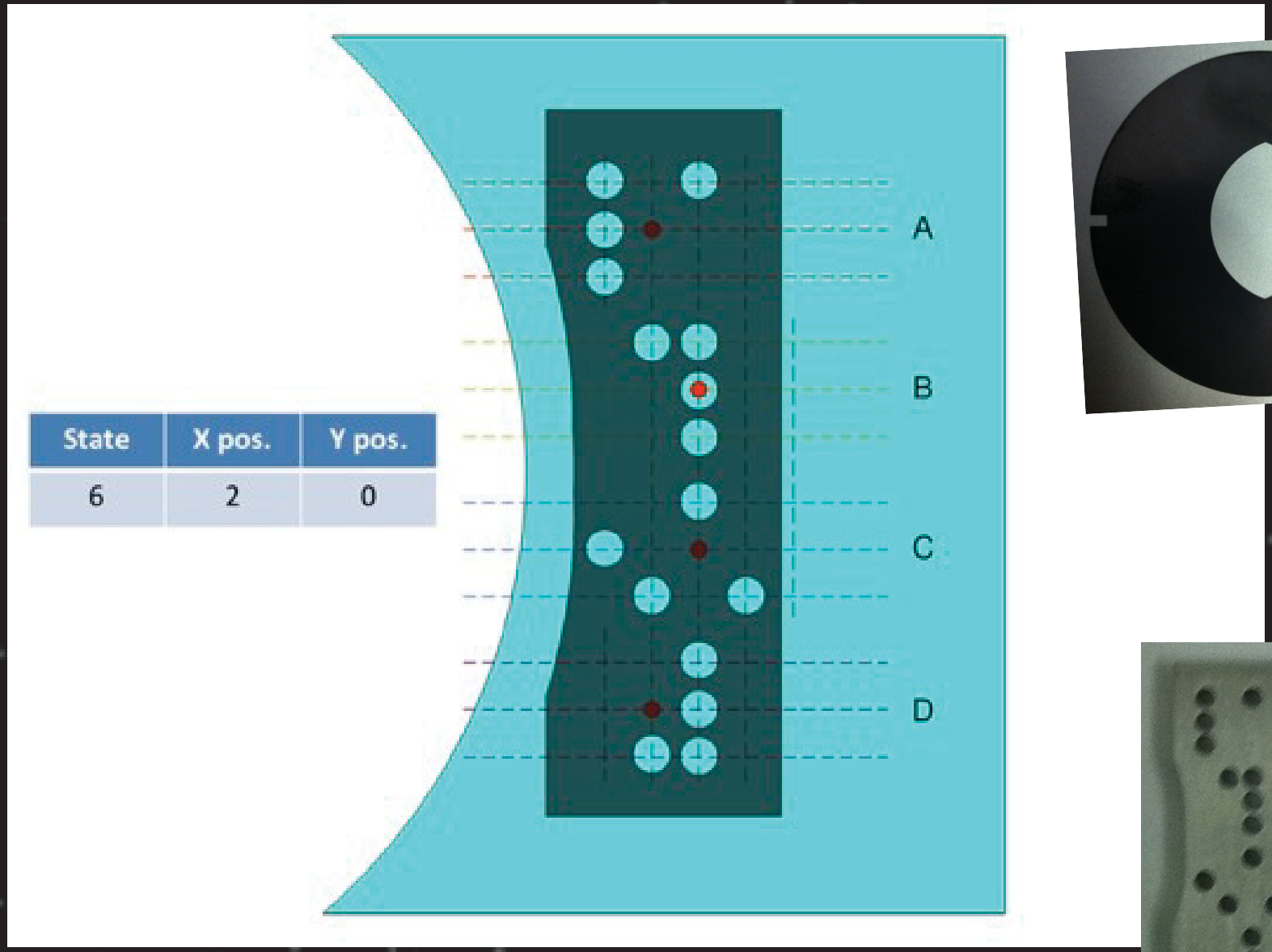




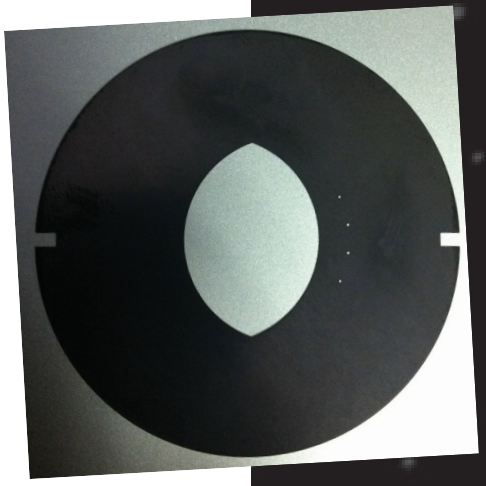


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Selecting the pinholes



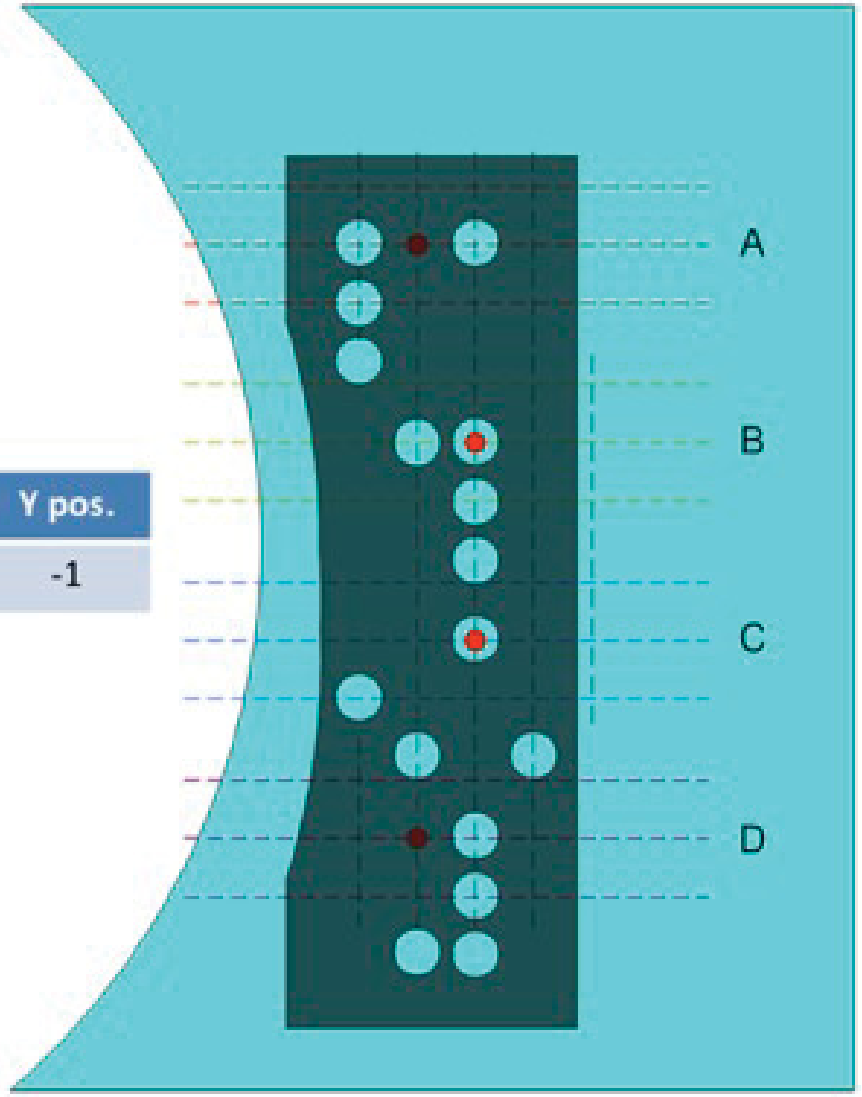
State	X pos.	Y pos.
6	2	0

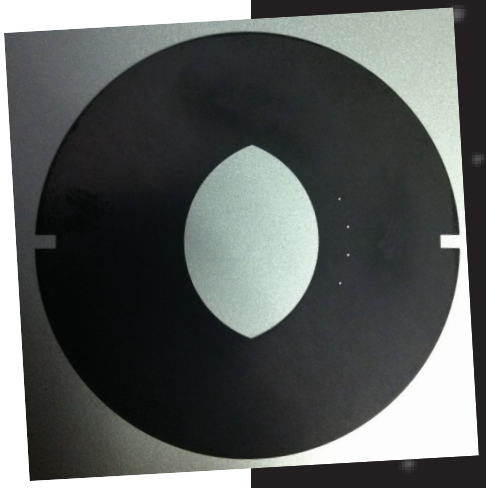


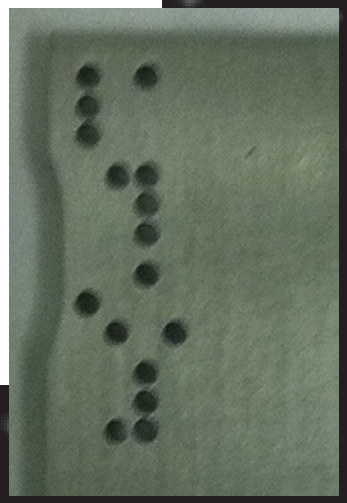
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

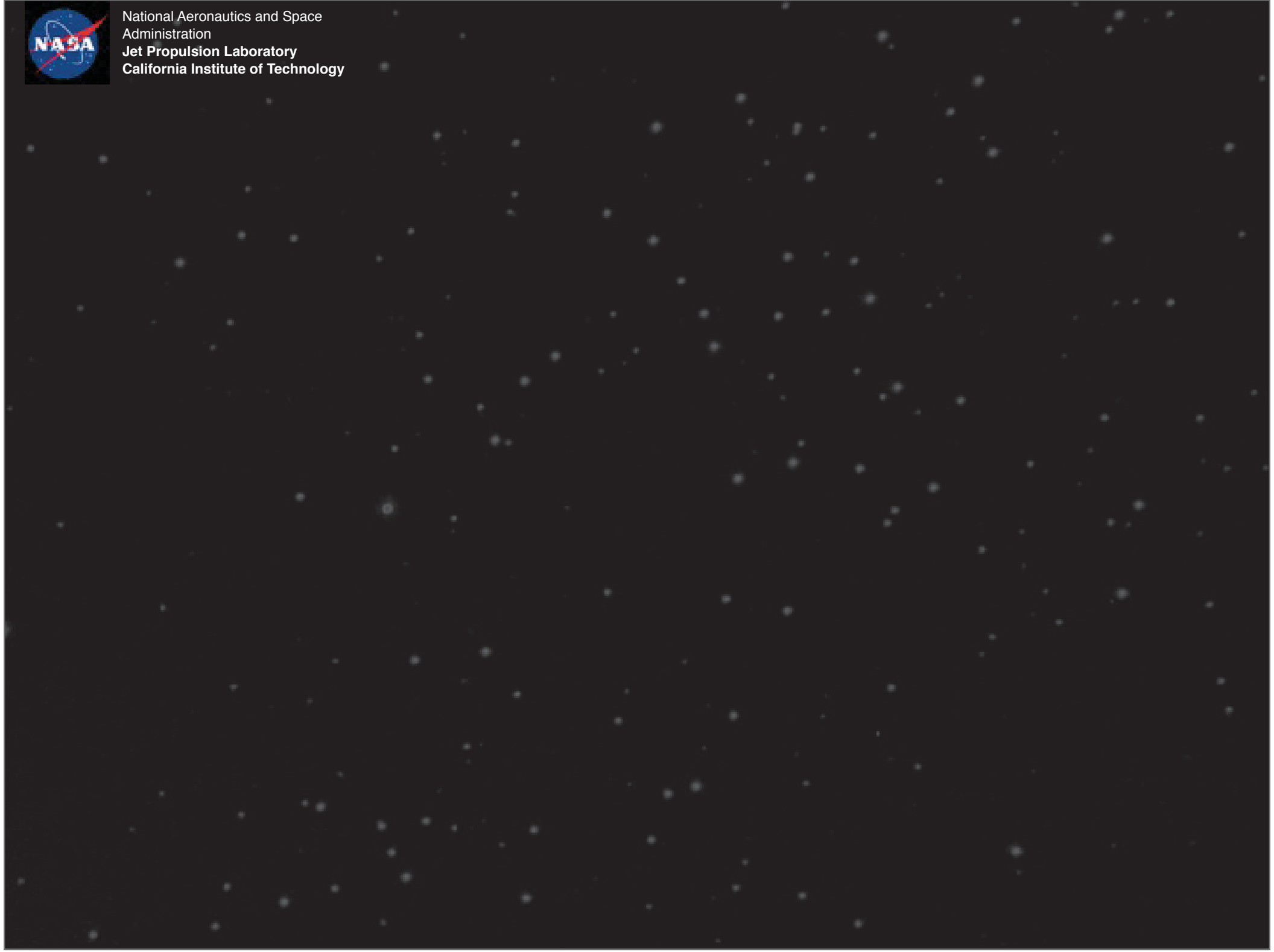
Selecting the pinholes

State	X pos.	Y pos.
7	2	-1



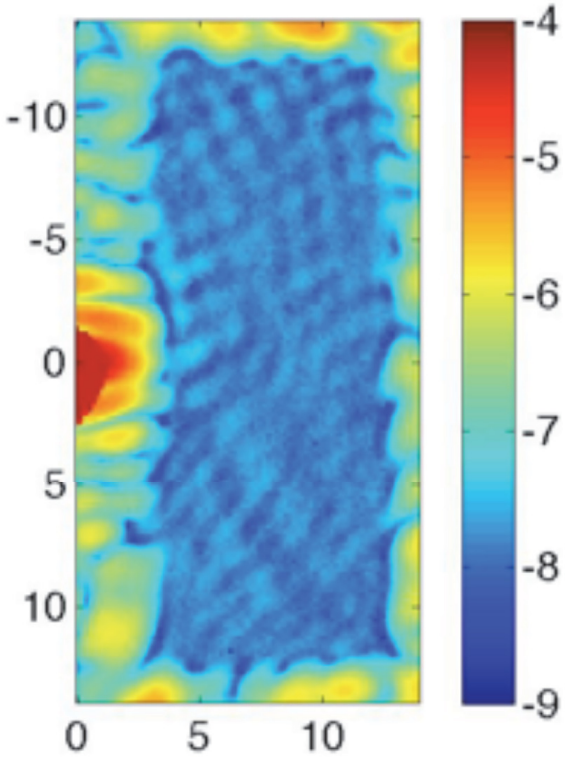






Monday, June 25, 2012

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

$$
\begin{aligned}
I_0 &= |E_0|^2 + I_{inc} \\
I_{oa} &= |E_0 + E_a|^2 + I_{inc} \\
I_{ob} &= |E_0 + E_b|^2 + I_{inc} \\
I_{oc} &= |E_0 + E_c|^2 + I_{inc} \\
I_{od} &= |E_0 + E_d|^2 + I_{inc}
\end{aligned}
$$

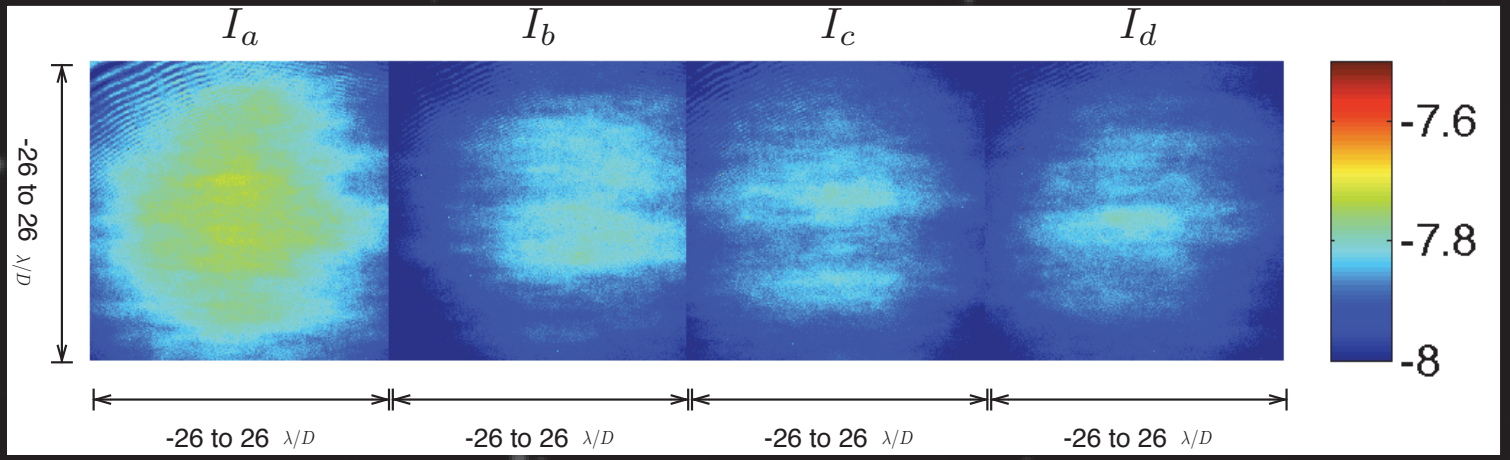
$$
\begin{bmatrix} \Re\{E_0\} \\ \Im\{E_0\} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -\Im\{E_a\} & \Re\{E_a\} \\ -\Im\{E_b\} & \Re\{E_b\} \\ -\Im\{E_c\} & \Re\{E_c\} \\ -\Im\{E_d\} & \Re\{E_d\} \end{bmatrix} \begin{bmatrix} I_{oa} - |E_a|^2 \\ I_{ob} - |E_b|^2 \\ I_{oc} - |E_c|^2 \\ I_{od} - |E_d|^2 \end{bmatrix}
$$

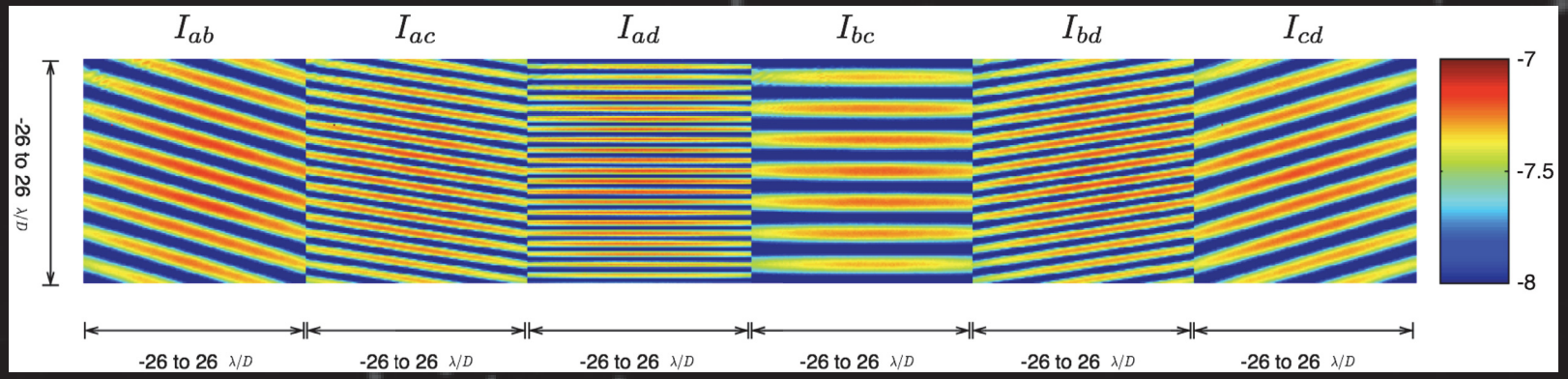
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Calibration model

$$
\begin{aligned}
I_a &= |E_a|^2 \\
I_b &= |E_b|^2 \\
I_c &= |E_c|^2 \\
I_d &= |E_d|^2 \\
I_{ab} &= |E_a + E_b|^2 \\
I_{ac} &= |E_a + E_c|^2 \\
I_{ad} &= |E_a + E_d|^2 \\
I_{bc} &= |E_b + E_c|^2 \\
I_{bd} &= |E_b + E_d|^2 \\
I_{cd} &= |E_c + E_d|^2
\end{aligned}
$$

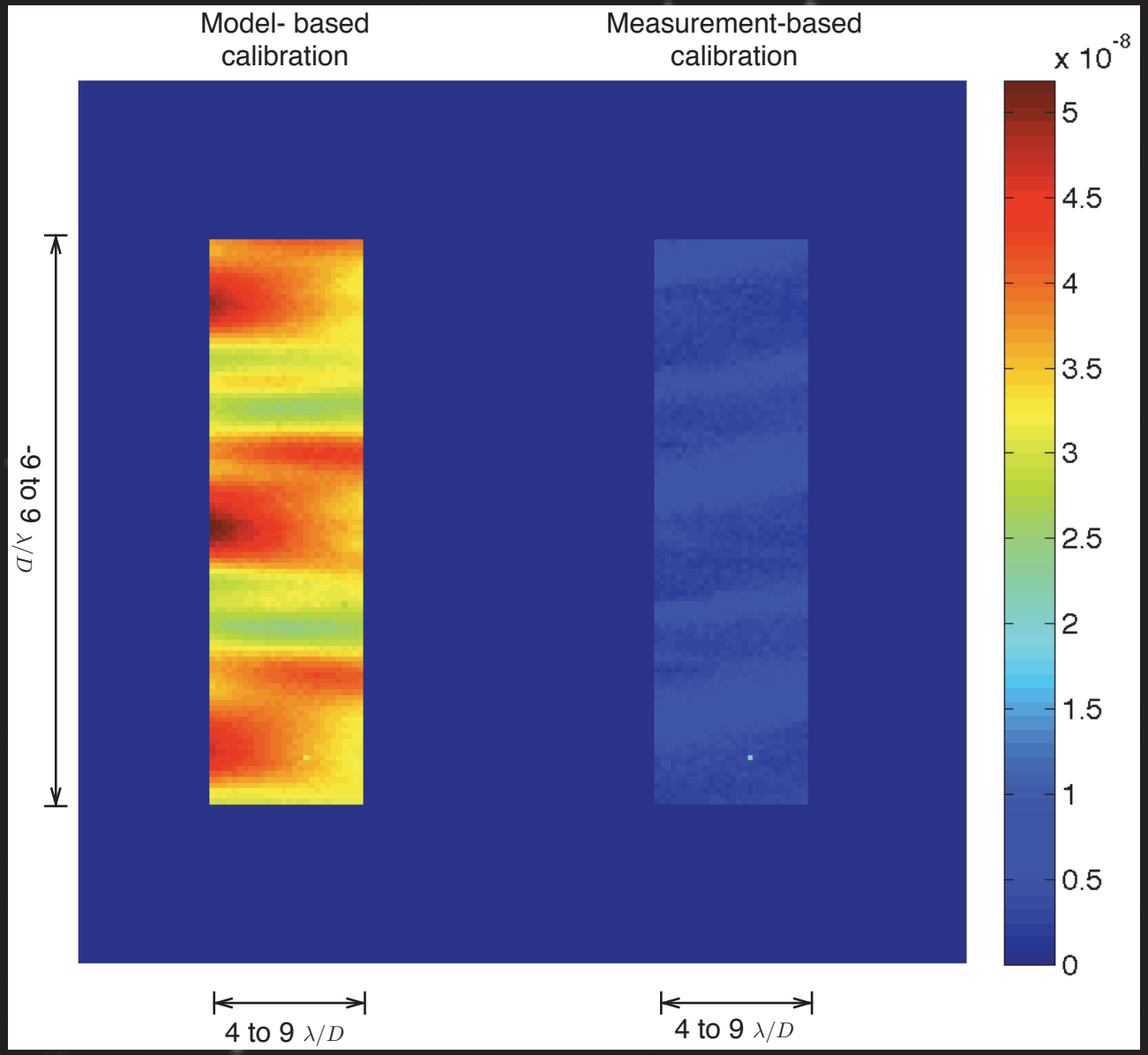
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



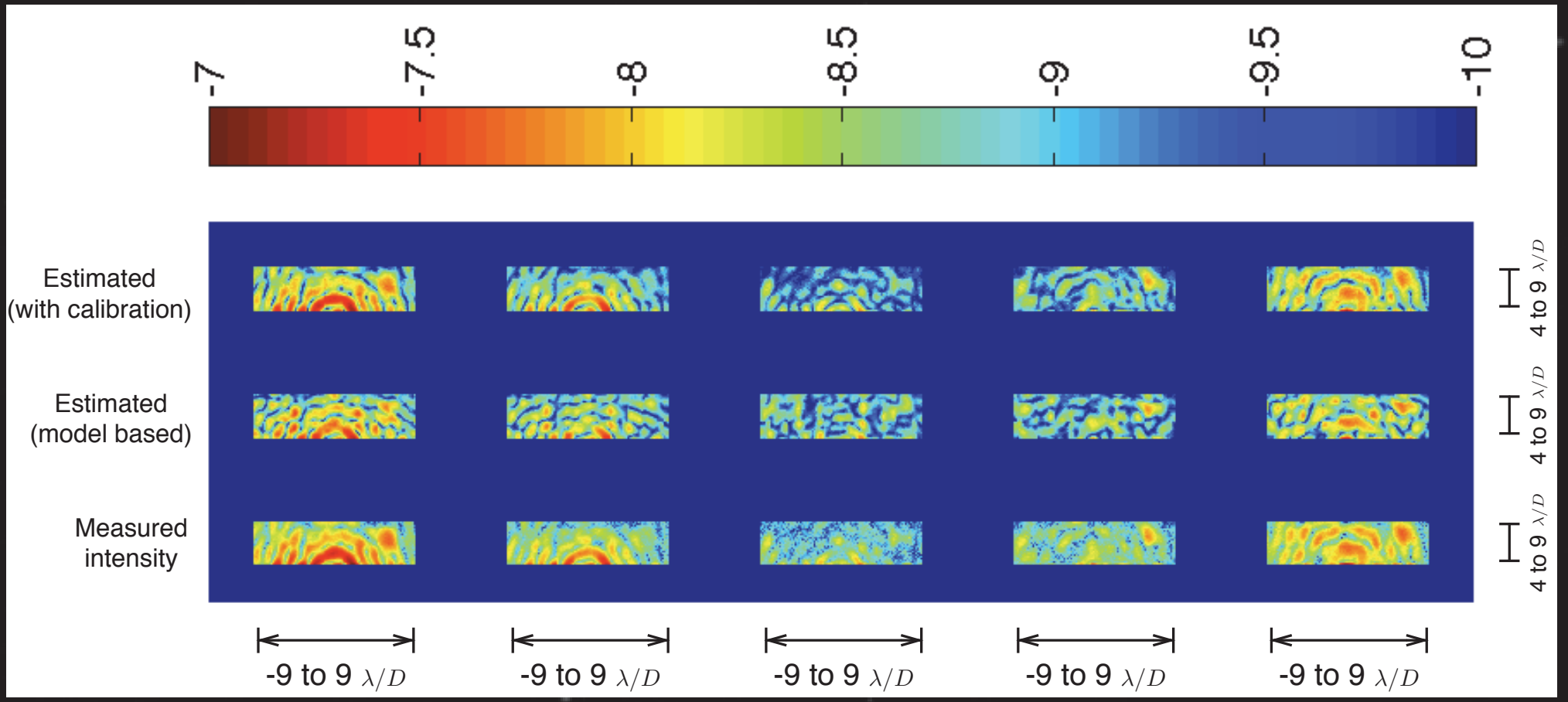


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

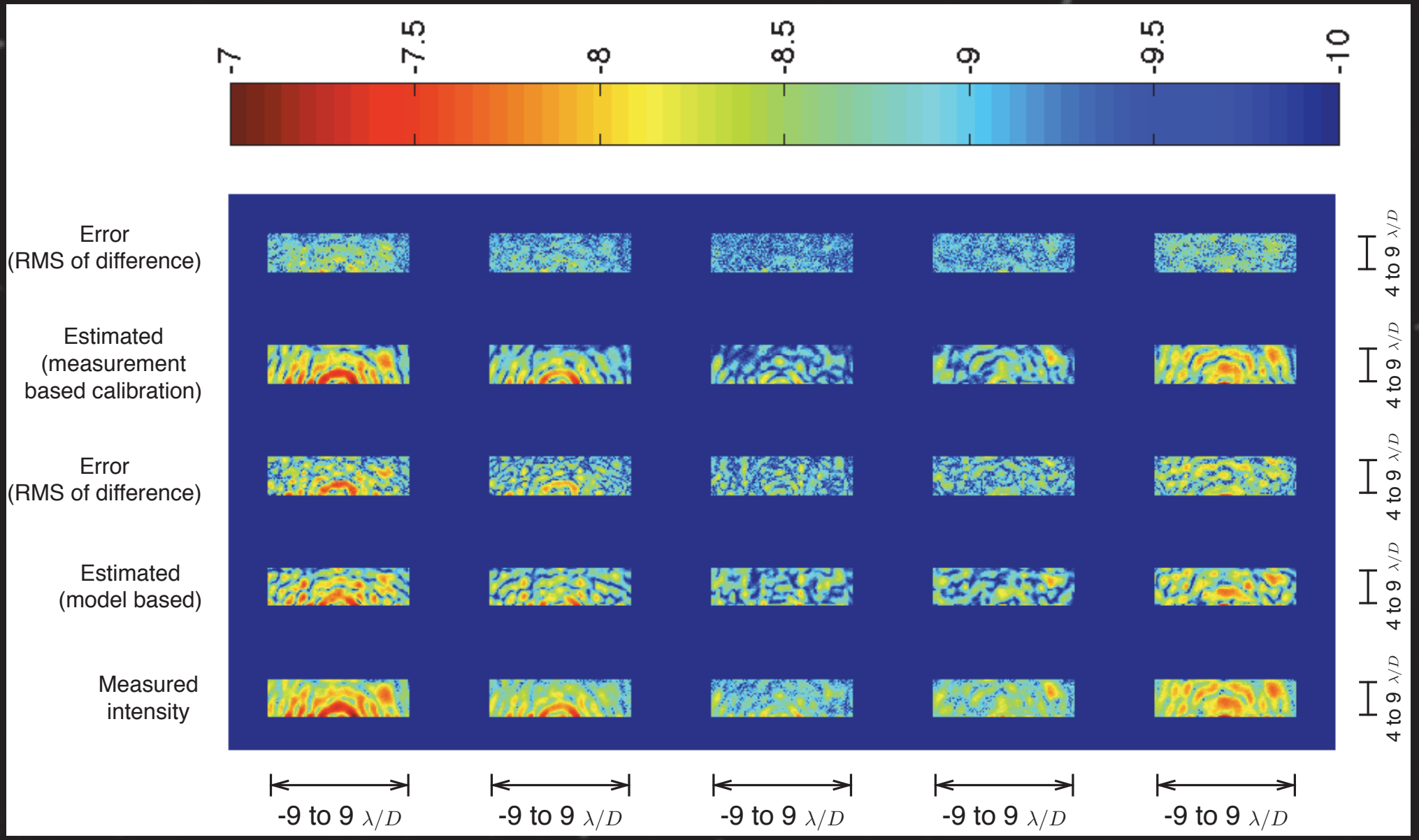
RMS improvement



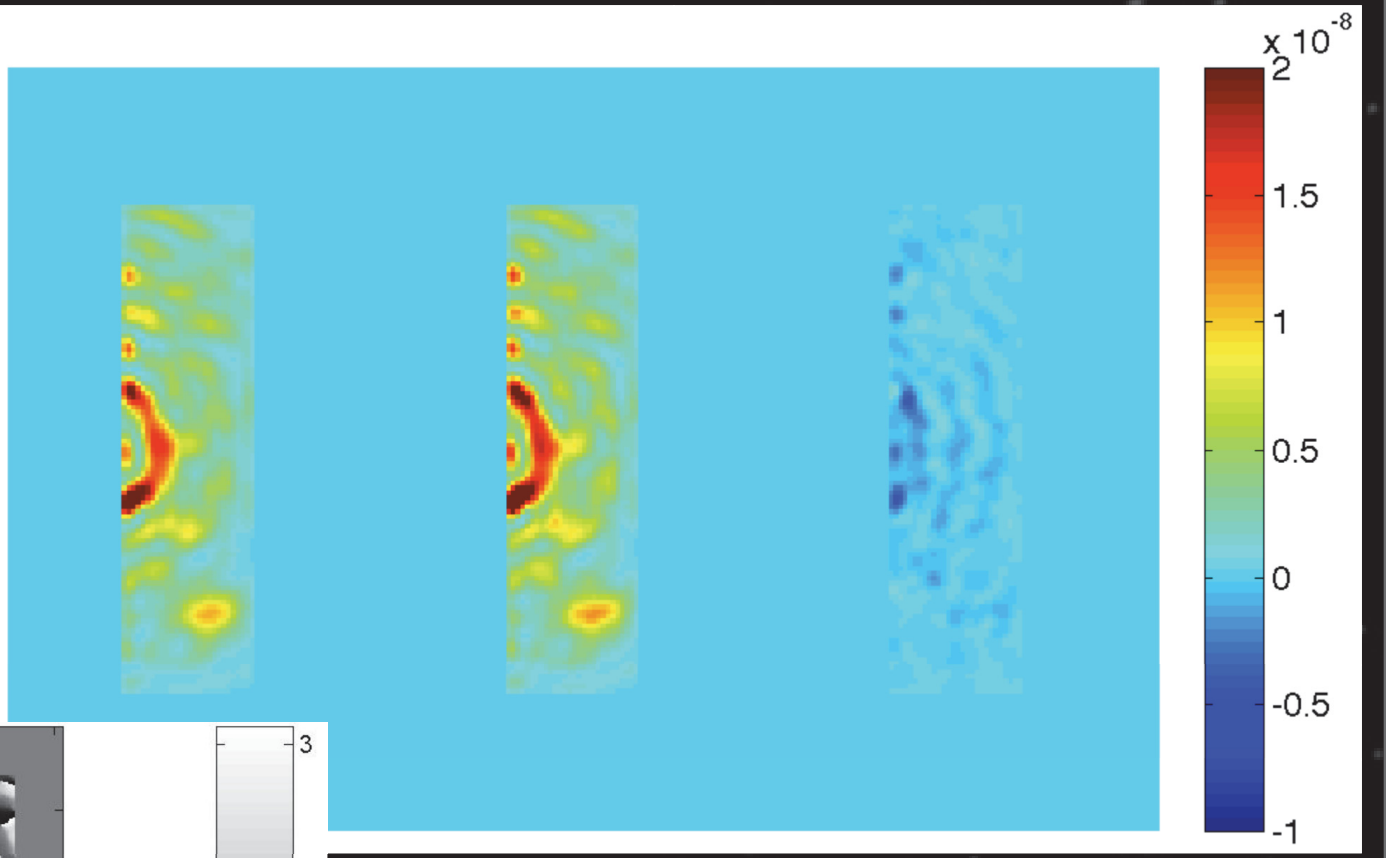
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

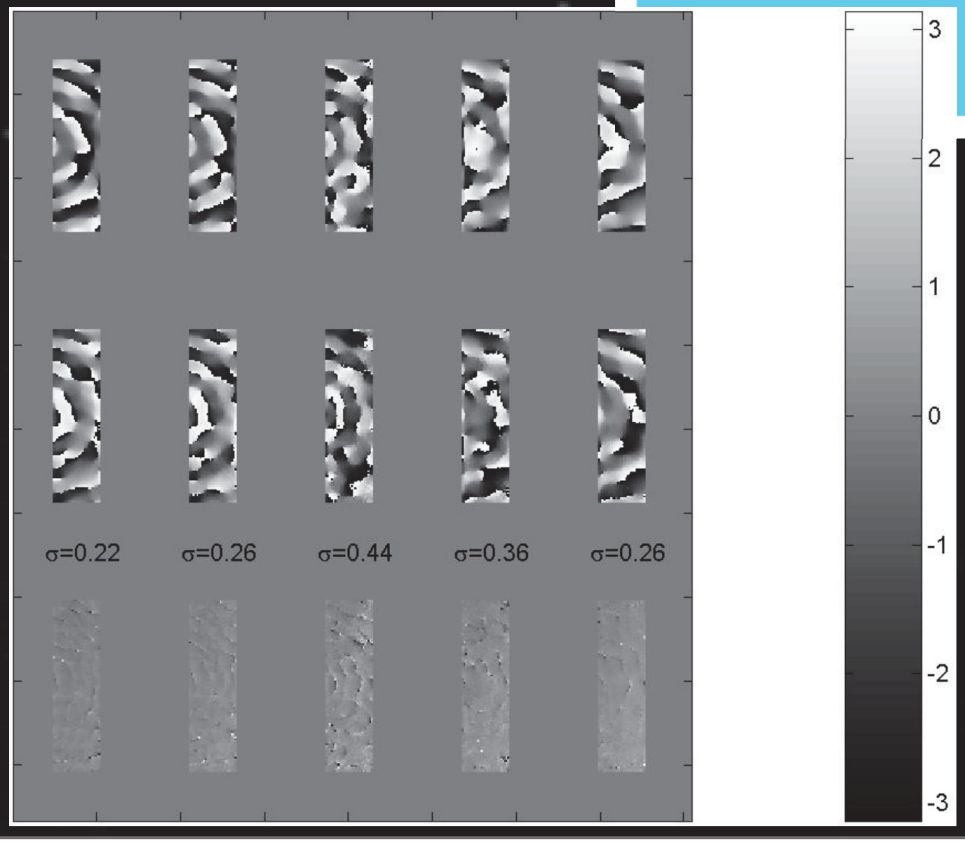


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology





Summary

- The pair-wise estimation has been used now on various testbeds with different coronagraphs with the best contrast results to date.
- Pinholes estimate has been implemented and ready to be tested in closed loop correction
- Pinholes estimate offers an independent method
- We hope to improve the calibration process to gain better estimates